Electrostatic Precipitator Transformer/Rectifier Evaluation Using Dissolved Gas-In-Oil Analysis

Abstract

Electrostatic precipitators (ESPs) are critical to the clean delivery of electric power as well as controlling particulate emissions from various industrial processes. The transformer/rectifier is a major component of the power supply system to the ESPs. The failure of a transformer/rectifier can limit the performance of the ESP system and in the case of a power plant ultimately limit the permissible output power of the station. As the Environmental Protection Agency enforces compliance with its Clean Air Act, the importance of the performance of the ESP transformer/rectifier has risen. This paper reviews a diagnostic analysis methodology based on oil analysis that is being developed to assess the condition of the Transformer/Rectifier.

Function of the Transformer/Rectifier

The basic function of the transformer/rectifier (T/R) is to provide a voltage source for the discharge electrodes of the electrostatic precipitator system. The major components of the complete ESP power supply system is comprised of voltage control circuitry, a current limiting reactor, the transformer/rectifier, and feedback signals from the T/R output back to the voltage control system.

The transformer/rectifier is a single-phase step-up transformer, plus high voltage diode bridge rectifier circuitry, housed in one tank. At times, the current limiting reactor, connected in series with the primary winding of the transformer, is also housed inside the same tank. The tank is typically filled with either mineral oil or silicone fluid. Typical ratings for a T/R are:

Input voltage = 400 V AC to 480 V AC (the power plant supply voltage)
Output voltage = 50 kV DC to 100 kV DC
Output current = 0.5 to 1.5 A DC
Power capacity = 50 kVA to 100 kVA

Figure 1 shows the basic arrangement of the ESP power supply components.

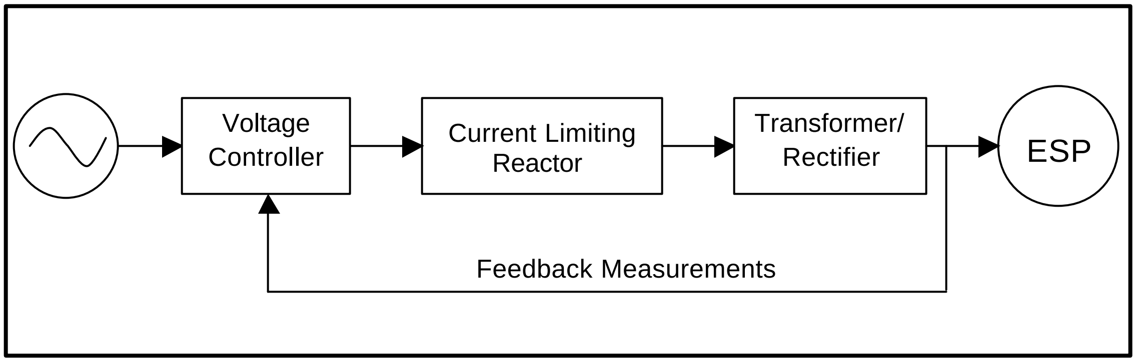

Figure 1: Block Diagram of ESP Power Supply System

Operation of the Transformer/Rectifier

Figure 2 shows a schematic diagram of the transformer/rectifier circuit.

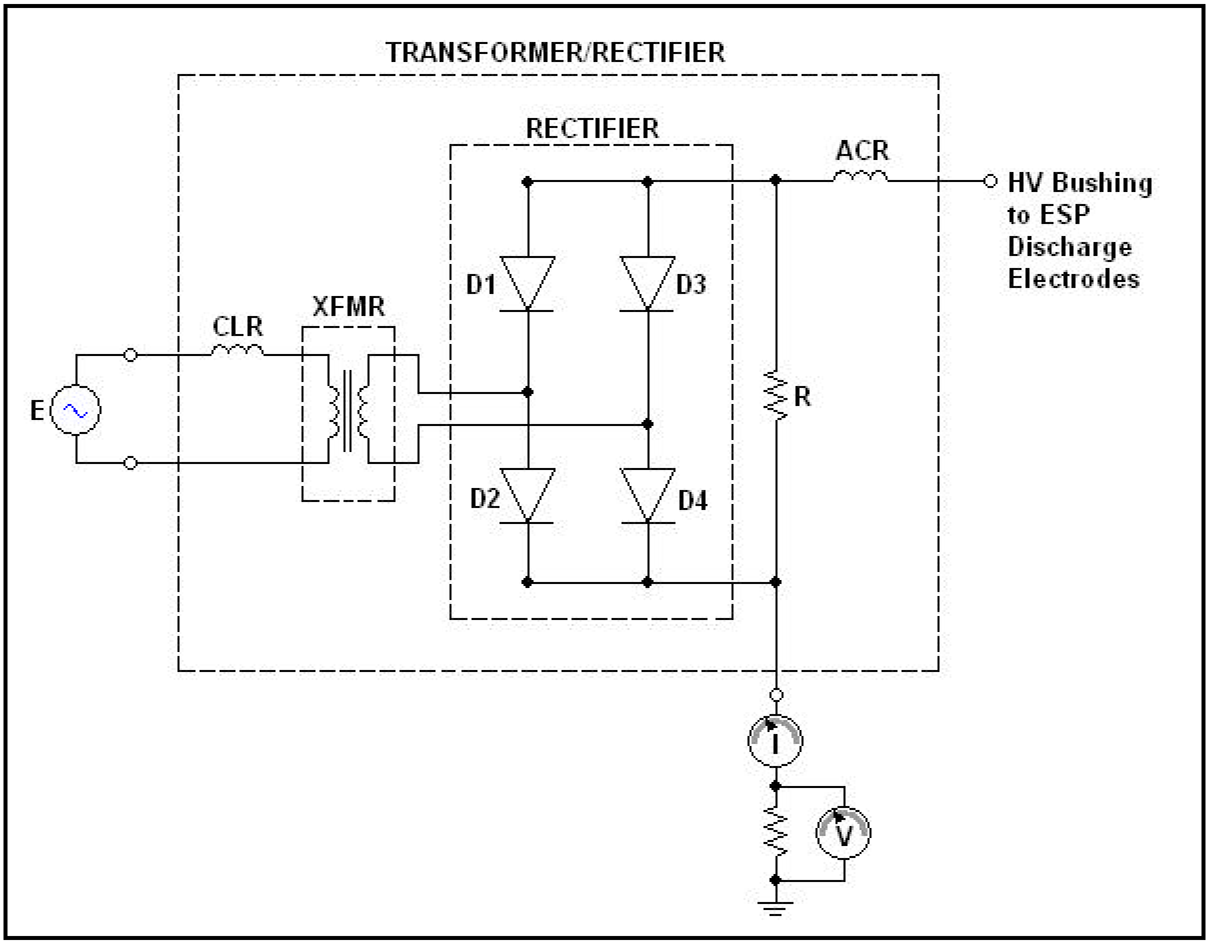

Figure 2: Transformer/Rectifier Circuit

The T/R receives a normal AC voltage and current as its power source, represented by “E” in Figure 2. The transformer of the T/R set is a simple single-phase, step-up transformer, which simply increases the supplied “E” voltage of approximately 480 V AC to the necessary high voltage for the operation of the ESP, approximately 50 kV AC to 100 kV AC. The “CLR” connected in series with the primary side of the transformer is a current limiting reactor. Its purpose is to limit short-circuit current (caused by the operation of the ESP) to approximately twice normal operating current.

The step-up transformer feeds its high voltage output to the input of the rectifier circuit. This common diode bridge rectifier circuit produces a rectified (DC) voltage, which is delivered to the discharge electrodes of the electrostatic precipitator. Figures 3a and 3b show a representation of the ideal voltage wave shapes at the input and output of the rectifier circuit.

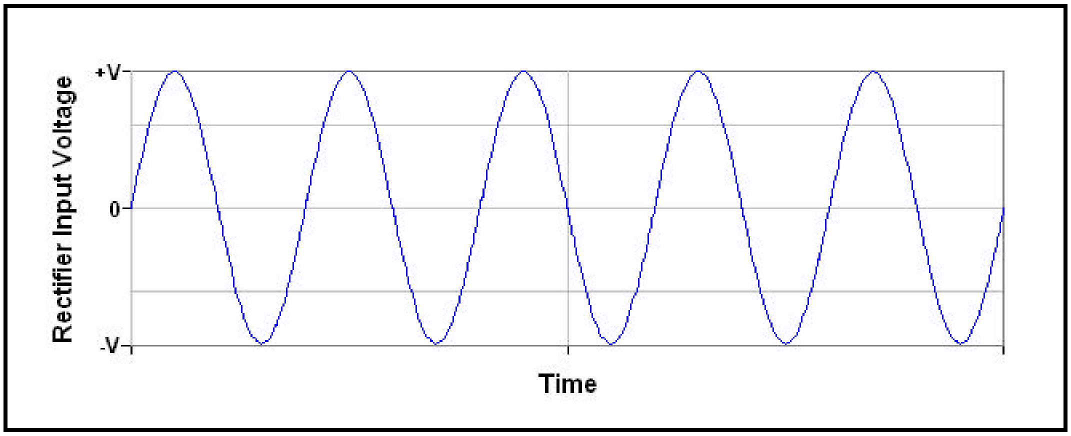

Figure 3a: Rectifier Input Voltage Wave Shape

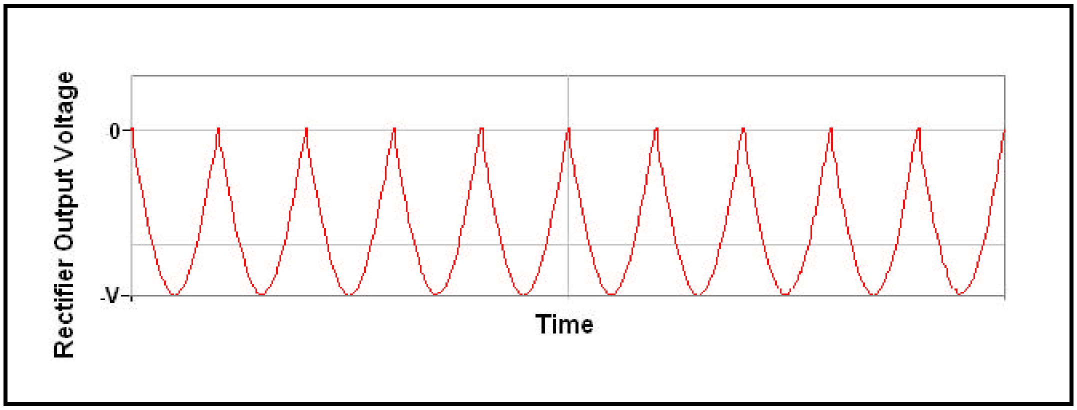

Figure 3b: Rectifier Output Voltage Wave Shape

The rectified voltage wave shape is produced by the configuration and operation of the diodes. No matter which one of the two input terminals of the diode bridge has the positive relative polarity, the output to the HV bushing always has a negative voltage to ground (a diode bridge has a positive and a negative side, and the negative side is commonly used for output to an ESP). This process is illustrated in Figures 4a and 4b. Figure 4a shows the rectifier circuit for the case when the upper input terminal (designated with a "+" sign) has a positive polarity relative to the bottom input terminal (designated with a "-" sign). In this case, diodes D2 and D3 conduct, while the other two diodes are effectively an open circuit. This creates the situation where the upper input terminal is essentially connected to ground through diode D2, and the lower input terminal hence produces a voltage negative to ground and delivers this to the HV bushing through diode D3.

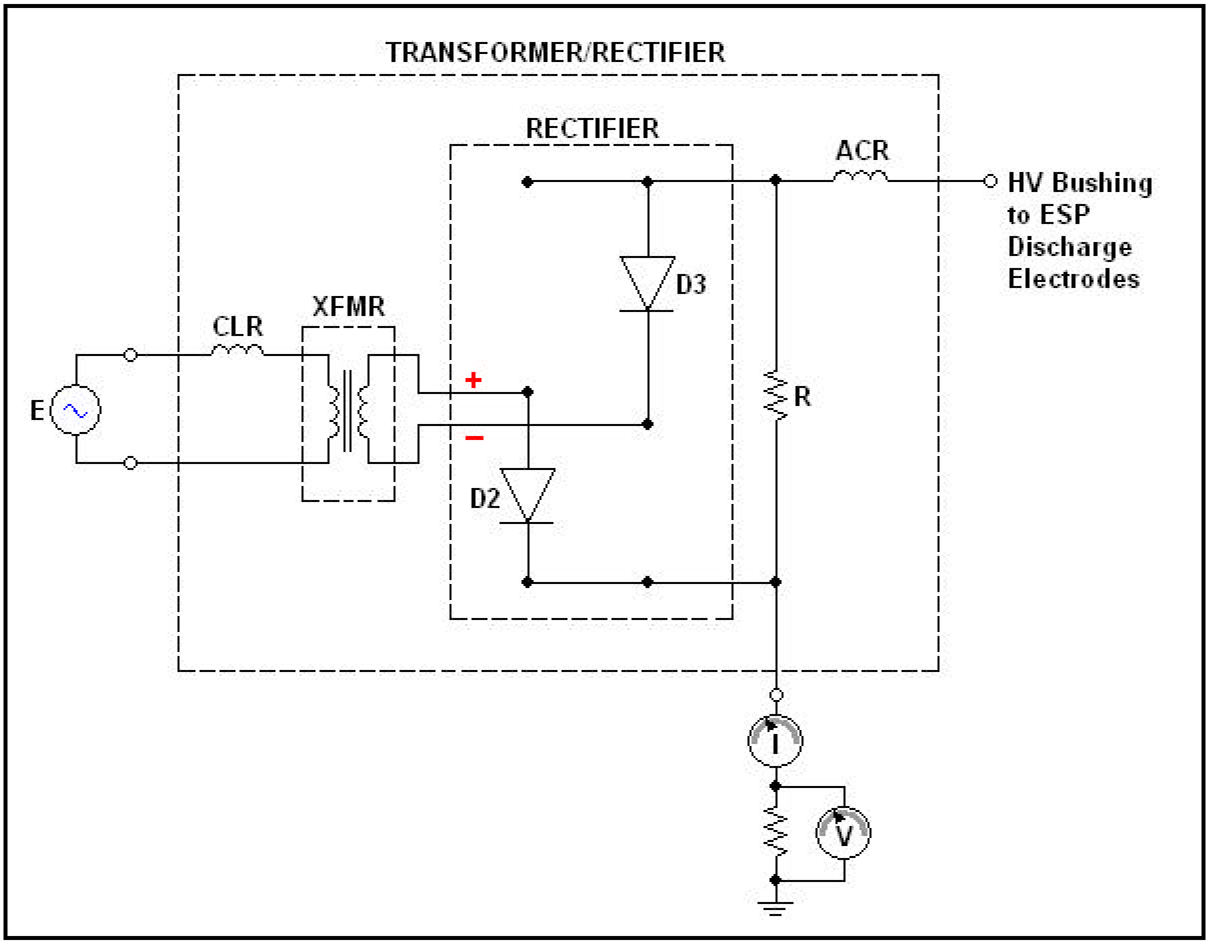

Figure 4a: T/R with D2 and D3 Diodes Conducting

Figure 4b shows the converse situation, when the upper terminal has a negative polarity relative to the bottom terminal. In that case, diodes D1 and D4 conduct. The lower terminal is now essentially connected to ground through diode D4, and the upper terminal hence produces a voltage negative to ground (since its voltage is negative relative to the lower terminal), and delivers this to the HV bushing through diode D1.

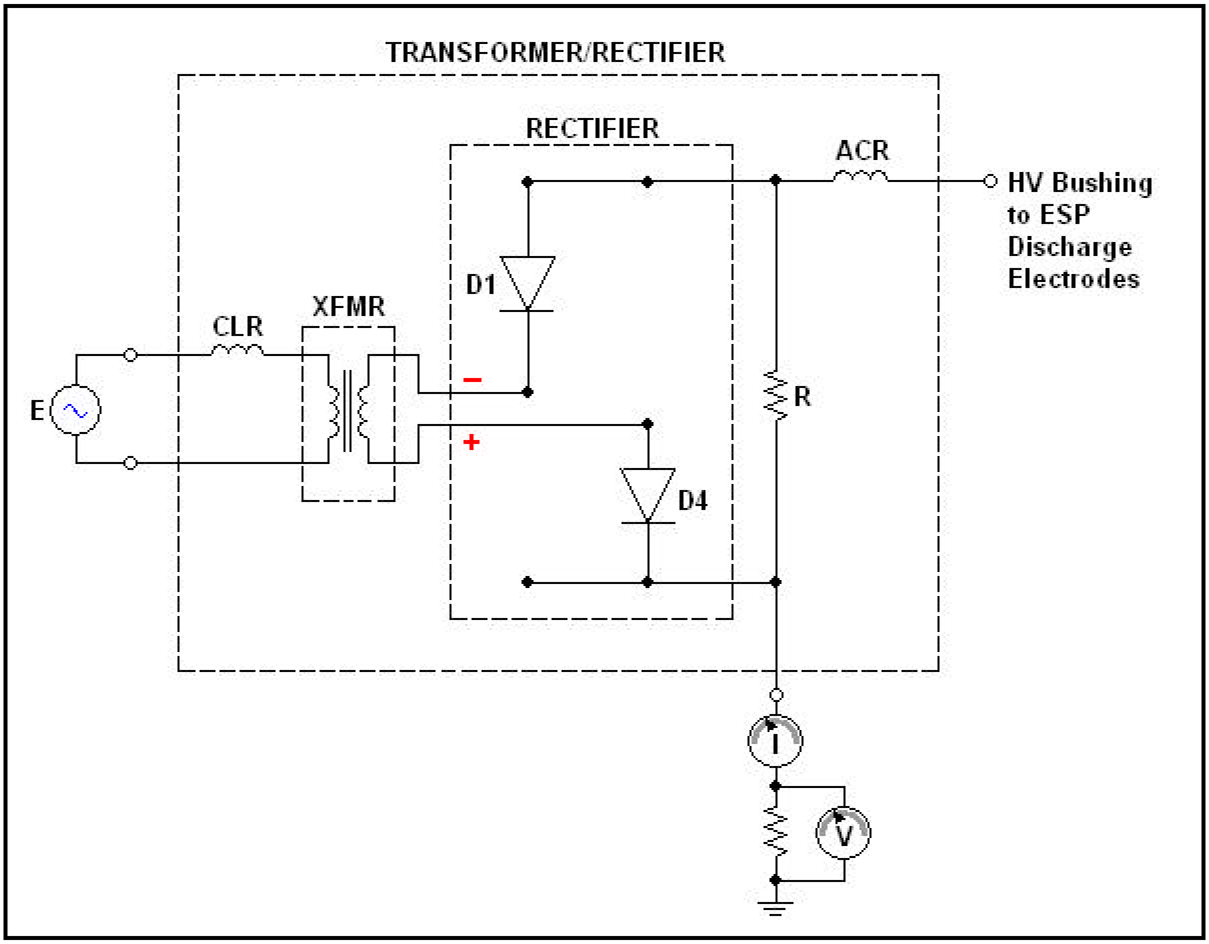

Figure 4b: T/R with D1 and D4 Diodes Conducting

This alternating between conducting pairs of diodes for each half-cycle of input voltage produces the output voltage wave shape shown in Figure 3b.

The “ACR” shown in Figures 2, 4a, and 4b is an air core reactor. The output connection to the ESP is subjected to sudden voltage drops due to the arcing and sparking happening inside the ESP. Particularly during arcing, this action is accompanied by rapid increases in current. By the presence of the ACR, these rapid changes are resisted, and results in a voltage drop across the ACR as the output changes suddenly from, for example, 50 kV to zero (when the short circuit occurs). Thus, the ACR protects the diodes from being subjected to sudden “dv/dt” voltage transients occurring as an effect of the ESP operation.

The resistor, R, shown in the same figures is a string of resistors (approximately 50 to 100 mega-ohms in total) simply acting as a voltage divider for the voltmeter shown further below in the schematic. The voltmeter and ammeter provide feedback information for the voltage controller (see Figure 1).

Failure Modes

As the various electrical components are submersed in the same mineral oil/silicone fluid inside the Transformer/Rectifier tank, one cannot be certain by only examining the DGA which component(s) may be the source of excessive gas. There are on-site electrical tests that can be performed to aid in the determination of the failed or malfunctioning component(s). A description of those tests is outside the scope of this paper. However, before choosing to take the T/R out of service in order to perform those tests, it is useful to be aware of the more common modes of failure that may contribute to the excessive gassing. This way, one can more intelligently prepare a case for taking the T/R out of service, and make a more informed choice of the tests to perform. In this section, some of the more common failure modes will be discussed.

It is important to note that the word “failure” in the term “failure mode” is somewhat of a misnomer. It does not necessarily mean that the T/R has ceased, or failed, to be operable. Indeed, DGA is best used to help identify incipient faults while the T/R is still in service. The word “failure” can be used to describe any component inside the T/R tank which may no longer be operating as intended, and hence failed, but the T/R as a whole may or may not still be operable.

When the DGA results show excessive gassing, the problem(s) causing the gassing can generally be categorized into three major groups:

1. Overheating
2. Partial discharges (“sparking” or “corona”)
3. Sustained discharges (“arcing”)

Here, possible causes of each are discussed briefly.

1. Overheating

All components of the T/R can be subject to overheating. One cause of overheating is overloading the T/R by having it power too many ESP discharge electrodes. In such a case, the current rating of the T/R may be exceeded, causing hotspots in the transformer windings, and thermal breakdown of the solid winding insulation over time. Also, the CLR (current limiting reactor) windings can similarly encounter overheating.

Another cause of overheating is due to the dynamic nature of the ESP load. There are occasional electrical arcs to ground between the negatively charged ESP discharge electrodes and its grounded collector plates. These arcs are literally load side short circuits, and are not interrupted by a load side circuit breaker (as would typically be the case for a normal power transformer). Instead, the arcs are quenched by the action of the automatic voltage controller (AVC) on the supply side of the T/R, which momentarily reduces the input AC voltage. But, if the AVC does not receive correct feedback signals from the load side voltmeter and ammeter, it will not adjust the input voltage to quench the arc in an appropriate amount of time. This results in a short-circuit current of excessive duration. Indeed, the CLR will limit the amplitude of the short-circuit current, but it cannot limit its duration. Thus, the CLR itself may receive severe thermal stress each time an arc occurs inside the ESP. The winding of the air core reactor may also be thermally overstressed depending on its designed current capacity.

However, perhaps the component most sensitive to the thermal stress of excessively long duration short-circuit currents is the diodes of the rectifier. Referring back to Figure 2, each of the diodes D1 through D4 shown in the schematic, are actually made up of a series string of many (usually dozens) of diodes. The solder joints connecting adjacent diodes can burn away due to the overheating caused by the short-circuit current. Or, the diode junction will overheat and fail to an open-circuit state. In either case, the voltage stress on the remaining diodes is increased. If enough diodes fail, and the resultant voltage stress on the other diodes is sufficiently high, a “domino effect” of failures can occur throughout the diode string, until the diode bridge is no longer operable.

The key gases produced from overheated components are methane, ethane, ethylene, and carbon monoxide.

2. Partial Discharges

As in normal power transformers, any electrical connection inside the T/R tank that is improperly made can produce partial discharges in the oil.

If the automatic voltage controller is not performing as intended, most components, including the transformer windings, CLR windings, air core reactor, and rectifier diodes, are susceptible to overvoltage, and hence partial discharges.

The air core reactor is particularly susceptible to partial or complete breakdown of its solid insulation. Referring to Figure 2, one can see that whenever the T/R load (the ESP discharge electrode) arcs to ground, then the load side of the ACR is grounded, while its other side connected to the output of the rectifier receives the full DC output voltage. So, the ACR insulation is highly dielectrically stressed. If its insulation begins to break down over time, partial discharges can result.

After complete failure of a diode junction, or during or after melting of its solder connection, significant partial discharge activity can also occur.

The key gas produced by partial discharges in the insulating liquid is Hydrogen.

3. Sustained Discharges (Arcing)

A common source of sustained electrical discharge, or arcing, inside a T/R comes from failing/failed diodes. As mentioned previously, the diode junction can fail to an open state, and its solder connection can melt, both due to overheating. In this process, arcing can occur either across the leads of the failed diode, or from the diode lead to the damaged or missing solder connection. As more diodes fail, in “domino” fashion, more arcing will occur.

In older T/Rs, the operational characteristics from one diode to another can vary enough to cause unequal sharing of the voltage across the series string of diodes. This can cause a diode to fail due to exceeding its Peak Inverse Voltage limit. This may in turn cause other diodes to fail as they receive an increased voltage as a result of the first diode failure. Arcs can be created with each diode failure. Newer diode designs tend to have very well controlled operational characteristics, and avoid this problem. Also, all diodes can be subject to overvoltage if the AVC improperly allows excessive output voltage.

Key gasses from arcing are acetylene and hydrogen.

Condition Assessment using Dissolved Gas-In-Oil Analysis Data

As various T/R component failures cause certain dissolved gases to appear in the insulating fluid, one can make use of quantitative guidelines for assessing the condition of T/Rs using DGA results. To establish such guidelines, a database containing several hundred T/R DGA test results was examined. This database was compiled from the lab test results from two oil laboratories. It is worthwhile to note that the majority of these test results (70 %) were from T/Rs built by one manufacturer. The remaining 30 % of the test results were from seven other manufacturers.

The dataset spanned nine years, from 1998 to 2007. For purposes of this study, the data was divided into two categories: T/Rs filled with mineral oil, and T/Rs filled with silicone fluid. This was done since some gases have a different solubility in silicone fluid than in mineral oil, for a given temperature and pressure. For mineral oil filled T/Rs, the database consisted of 519 oil samples, from a total of 398 T/Rs. For silicone fluid filled T/Rs, the database consisted of 340 fluid samples from a total of 287 T/Rs. Of the T/Rs with a kVA recorded, the dataset varied from 24 kVA to 115 kVA. Of the T/Rs with a primary voltage recorded, the dataset varied from 400 V to 480 V.

A summary of the DGA data follows.

PPM DISSOLVED GAS IN MINERAL OIL							
	H2	**CH4**	**C2H6**	**C2H4**	**C2H2**	**CO**	**CO2**
AVERAGE	68	182	192	495	37	304	3312
MEDIAN	19	10	3	5	0	243	2364
MAX	5953	44752	86103	170142	6873	4744	21689
2^{ND} MAX	2710	37793	7934	74292	6834	2731	17388
98^{TH} %	307	143	101	189	152	1100	11465
90^{TH} %	120	41	24	45	4	670	7271
MIN	0	0	0	0	0	1	35

Note: "MAX" is the maximum value in the dataset. "2nd MAX" is the next-to-maximum value in the dataset. "98th %" is the 98th Percentile value. "90th %" is the 90th Percentile value. "MIN" is the minimum value in the dataset.

Table 1: Summary of DGA Data for Oil-Filled T/Rs

PPM DISSOLVED GAS IN SILICONE FLUID							
	H2	**CH4**	**C2H6**	**C2H4**	**C2H2**	**CO**	**CO2**
AVERAGE	134	291	66	75	3	1349	10372
MEDIAN	23	34	7	2	0	1406	9135
MAX	9822	38108	3168	3879	400	11163	29755
2^{ND} MAX	7665	12726	3015	3529	204	5511	29323
98^{TH} %	776	2226	1018	1419	12	3875	27186
90^{TH} %	160	188	30	26	2	2604	21991
MIN	0	0	0	0	0	1	85

Note: "MAX" is the maximum value in the dataset. "2nd MAX" is the next-to-maximum value in the dataset. "98th %" is the 98th Percentile value. "90th %" is the 90th Percentile value. "MIN" is the minimum value in the dataset.

Table 2: Summary of DGA Data for Silicone Fluid-Filled T/Rs

For each of the above tables, note that the "MAX" gas quantities did not necessarily come from the same oil sample. For example, the "MAX" H2 quantity may have come from a different oil sample than the "MAX" CH4 quantity. The same possibility applies for the "2nd MAX", "98th %", "10th %", and "MIN" quantities for each gas.

From the above data it was seen that in most cases there was a significant difference between the 98th Percentile values and the maximum or next-to-maximum values for each gas. This implies that the maximum, next-to-maximum, and possibly additional data values are likely statistical "outliers" (data points that are well outside the range of values of the vast majority of the other data points), and can be excluded from the dataset that will ultimately be used to establish gas limits from which to interpret the equipment condition. More about the determination of outliers will follow later.

With the dataset, or sample set, established, one can apply methods to process the raw data into a meaningful statistical distribution of values. From that distribution the value limits can be chosen which will classify gas values into categories of “Good,” “Caution,” and “Warning.” The method chosen in this study was to transform the raw data for each individual gas into a distribution resembling a normal distribution, and choose the three aforementioned gas categories from that distribution. This method was comprised of the following steps:

1. For a given gas, calculate the natural logarithm of each of the raw data values.
2. Apply rules to the distribution of these transformed values to identify and exclude outlier values.
3. With outliers removed, use the interquartile range of the distribution to reconstruct a normal distribution.
4. Choose the “Good,” “Caution,” and “Warning” value limits from the normal distribution.
5. Calculate the inverse logarithm of the values chosen in step 4. These are the final “Good,” “Caution,” and “Warning” limits, in ppm, for the given gas.

The appeal of the above approach is not a scientific exactness, but rather a repeatable procedure, whose rules can be applied and followed for each gas, for both the oil-filled, and silicone fluid-filled T/Rs. Another appeal of this approach is that it lends itself well to being programmable.

Using dissolved Methane (CH4) gas-in-oil as an example, the aforementioned method is illustrated in detail as follows:

Firstly, the sample data was chosen. In this case, it was a dataset of 519 values of Methane gas quantities, expressed in parts-per-million, taken from the DGA test results of oil-filled T/Rs. The following “Probability Plot” shows each ppm value in the sample data vs. the percentage of values in the sample data that are less than or equal to it. Looking at the plot, it was clear that there were at least two outlier values from the bulk of values in the sample data.

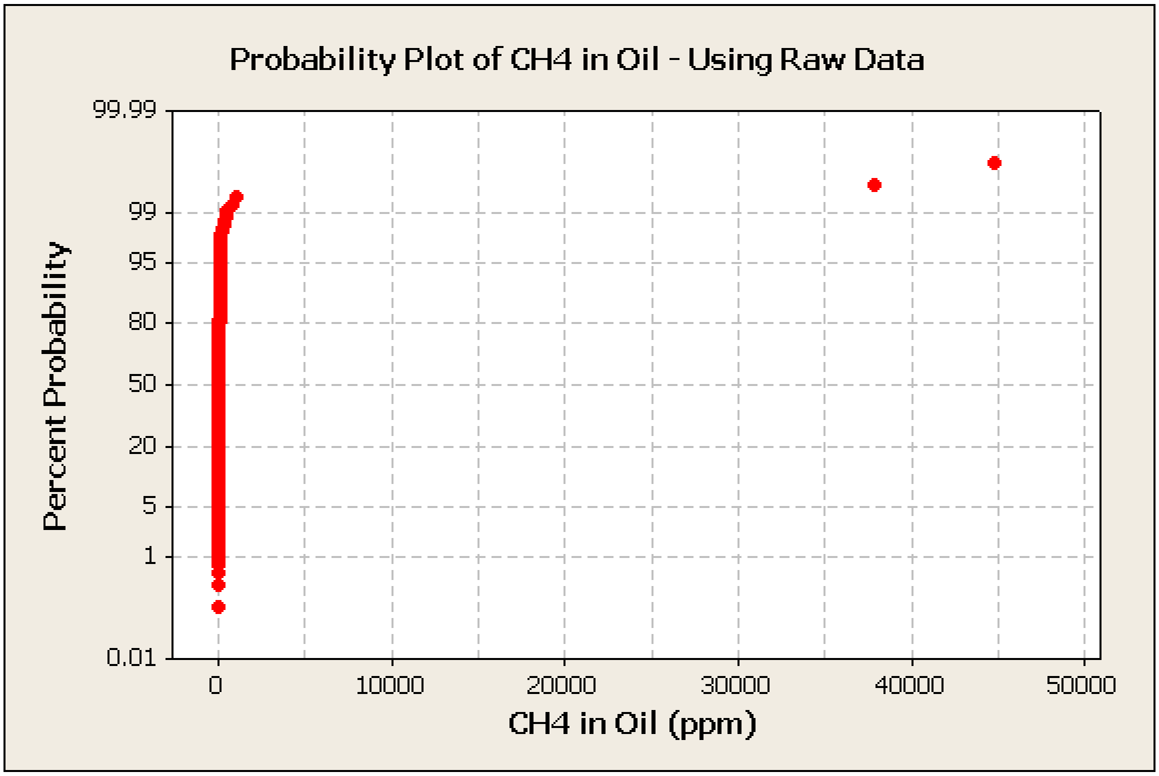

Figure 5: Probability Plot of CH4 from DGA Data for Oil-Filled T/Rs

For the sole purpose of examining with more detail the Probability Plot for the bulk of the sample data, these two outlier values were removed. The resulting plot is shown in Figure 6. Also shown in the same graph is a "best fit" normal distribution curve (appearing as the blue line). This best fit curve was calculated by "Minitab," a widely used statistical software program. By visual examination alone, it was obvious that the raw dataset (minus two outliers) did not approximate a normal distribution at all.

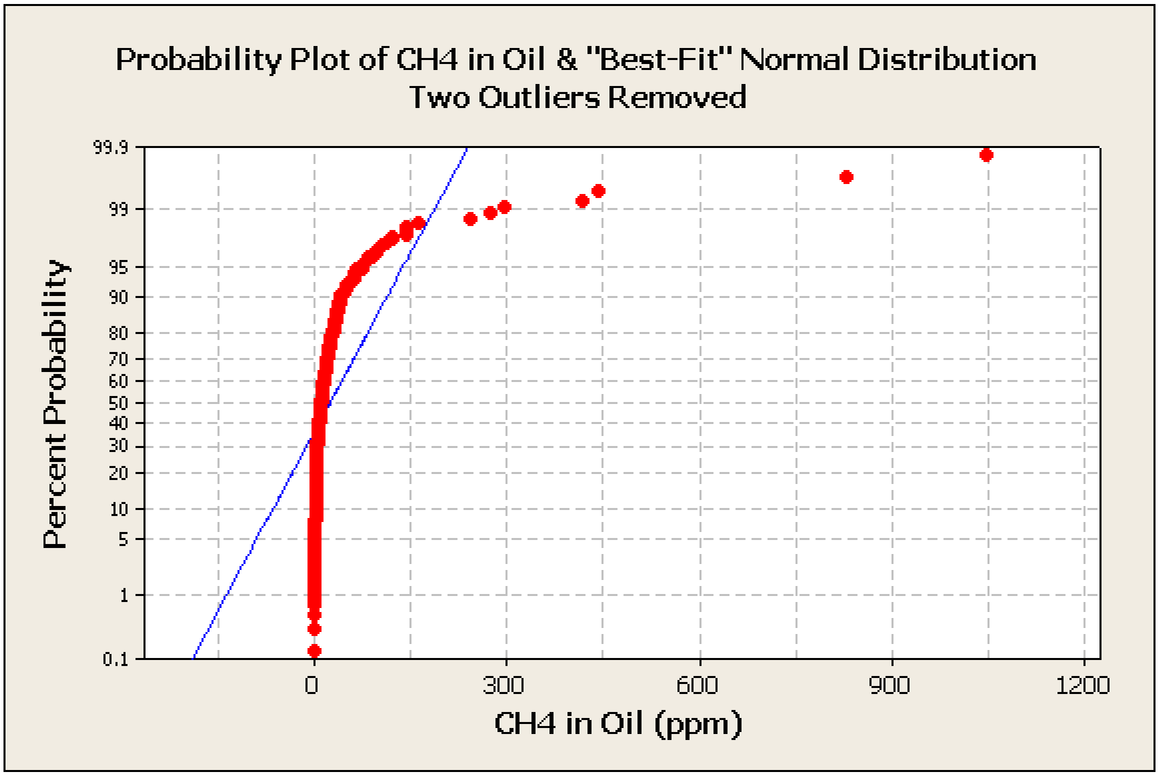

Figure 6: Probability Plot of CH4 & "Best-Fit" Normal Distribution, 2 Outliers Removed

By simply transforming the raw data values (in ppm) into their natural log values, the distribution of the values follows a normal distribution quite closely. That is, a "lognormal" distribution becomes evident. Figure 7 shows the distribution of the natural logarithm of the data values, as well as the "best fit" normal distribution (shown in blue), as calculated by the "Minitab" program.

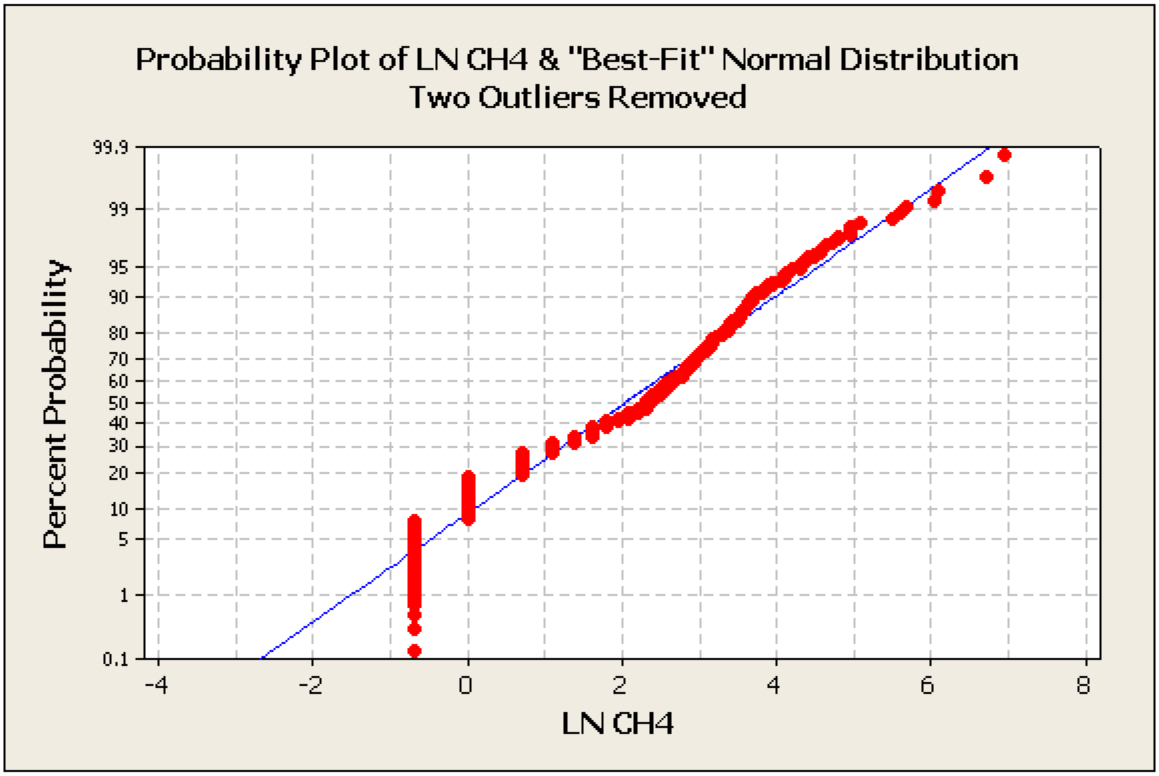

Figure 7: Probability Plot of Ln of CH4 & "Best-Fit" Normal Distribution, 2 Outliers Removed

Since the data values follow a lognormal distribution, some commonplace statistical guidelines can be followed to systematically remove outlier values from the dataset. With the outliers removed, and using the bulk of the data between the first and third quartiles of the distribution, a new lognormal distribution can be constructed. From that, the "Good," "Caution," and "Warning" value limits can ultimately be chosen.

With this approach in mind, we can now proceed to systematically remove the outlier values from the original dataset, and construct a new lognormal distribution. To do so, we will take one step back, and return to the natural logarithm values based on the original dataset, but with all outliers included.

The distribution of the natural logarithm values, with all outliers included, is shown in Figure 8, along with its best fit normal distribution curve. Note that this figure is similar to Figure 7, except the two outlier values, which were previously removed, are now included again. Note that in order to plot the natural log of the zero ppm data points, these zero values were replaced by 0.5 ppm, whose natural log values then became ln(0.5) = -0.6931.

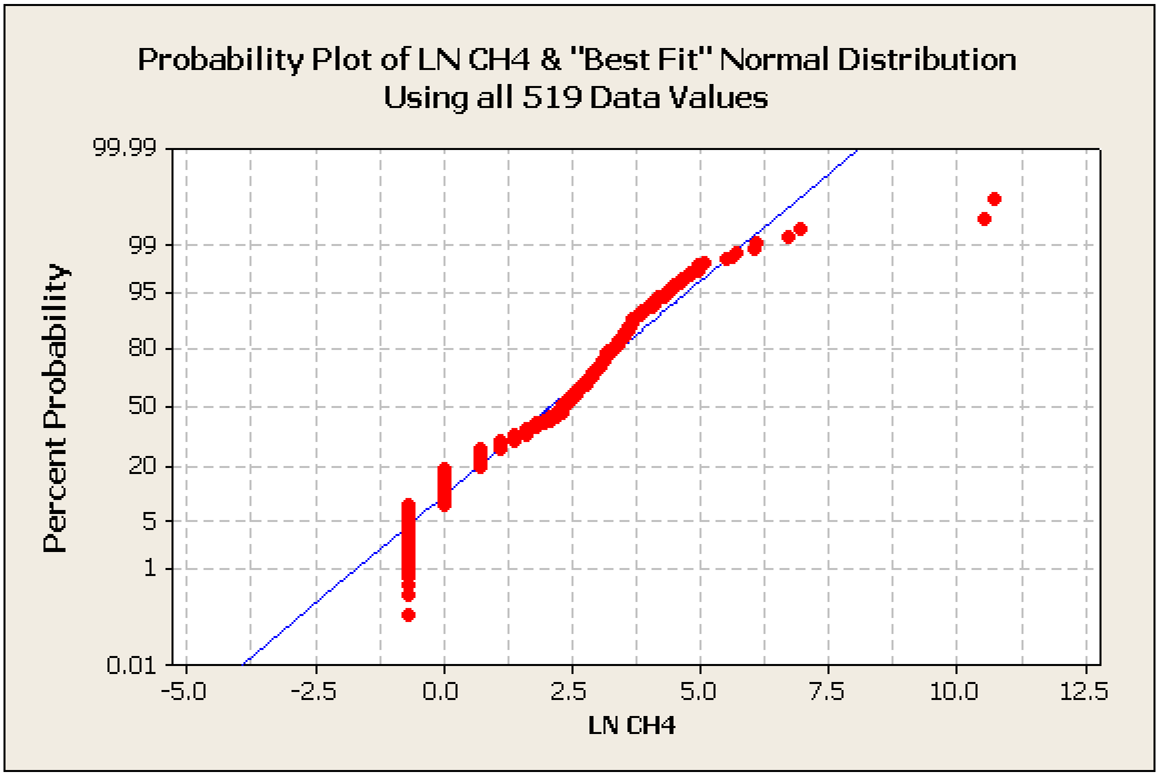

Figure 8: Probability Plot of Ln of CH4 & "Best-Fit" Normal Distribution, All Outliers Included

Using the dataset of natural log values, whose distribution is represented by the red dots in Figure 8, the following calculations were made (this method is similar to that currently being proposed to be included in IEEE Std C57.139):

- The third quartile point of the distribution ("Q3")
- The median point of the distribution ("Mdn")
- The interquartile range ("IQR", where IQR = (Q3 – Mdn)*2)
- The upper outlier rejection limit ("U1", where U1 = Q3 + 1.5*IQR)

Using the complete dataset of 519 natural log values (calculated from the original CH4 ppm values), these calculations provided the following results:

Q3 = 3.14
Mdn = 2.30
IQR = (3.14 – 2.30)*2 = 1.68
U1 = 3.14 + 1.5*1.68 = 5.66

At this point, the important number was U1, the upper quartile rejection limit. All of the natural log values in the dataset greater than U1 were removed from the distribution. Then, Q3, Mdn, IQR, and U1 were recalculated. This iterative process continued until all natural log values remaining in the distribution were less than U1. At the conclusion of this process, the final distribution had the following characteristics:

Q3 = 3.09
Mdn = 2.30
IQR = 1.58
U1 = 5.46

The final number of natural log values remaining in the distribution for CH4 was 510, meaning that 9 “outlier” values had been removed. Figure 9 shows this distribution, along with its “best fit” normal distribution.

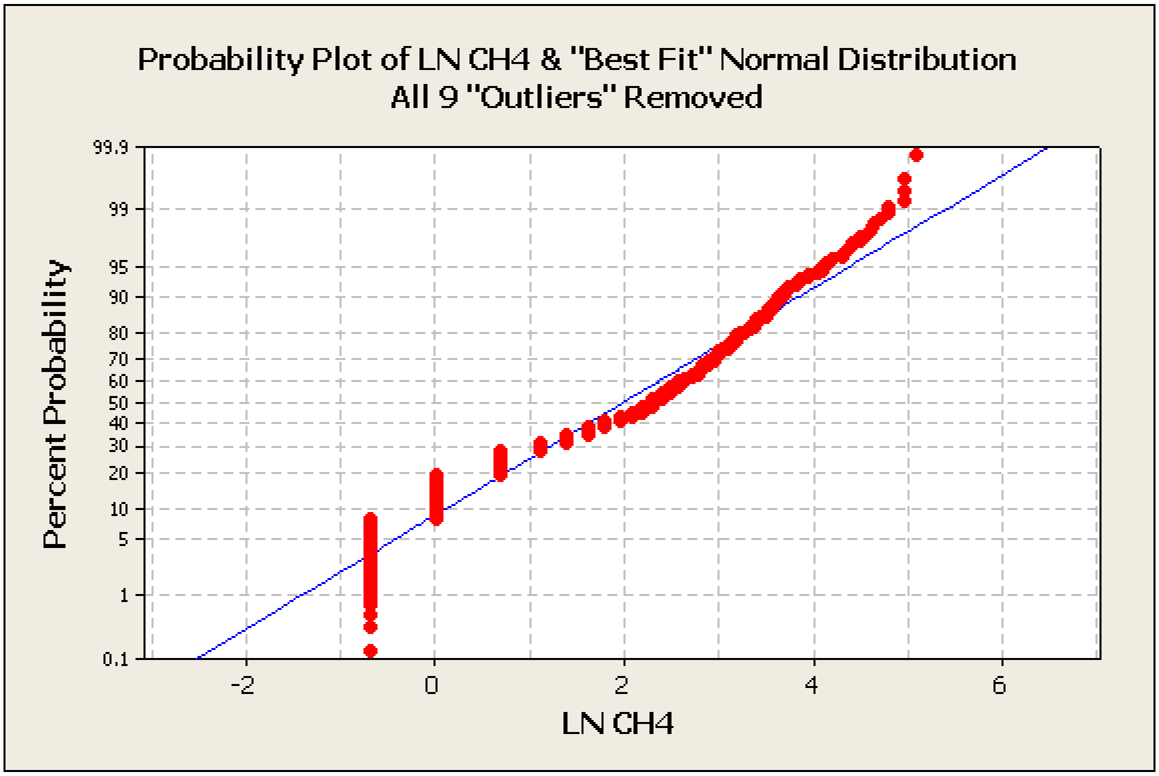

Figure 9: Probability Plot of Ln of CH4 & “Best-Fit” Normal Distribution, All 9 “Outliers” Removed

Note that the “best fit” normal distribution in Figure 9 was strongly influenced by the low Ln(CH4) values, that is, the –0.6931, 0, and +0.6931 values. These values correspond to the 0.5 ppm, 1 ppm, and 2 ppm CH4 values prior to converting them to the natural log values. If the gas chromatogram measuring the quantities of dissolved gasses in the oil could accurately measure to the nearest 0.1 ppm, we could likely have a distribution of values between 0 ppm and 2 ppm much more closely following a lognormal distribution. That is, the distribution of the natural log of the ppm values between 0 ppm and 2 ppm measured in 0.1 ppm increments, would much more closely follow the best fit normal distribution. However, in reality, we had measurements rounded to the nearest 1 ppm, which introduced significant percent error in the 0 ppm to 2 ppm measurement range. In other words, this rounding resulted in a large number of 0 ppm, 1 ppm, and 2 ppm discrete values, rather than being lognormally distributed values in 0.1ppm increments. Nevertheless, it was vitally important to use these values to ascertain decent values for Q3 and the median, and subsequently the interquartile range and U1. However, with the interquartile range calculated, and by reasonably assuming that the interquartile range (and the rest of the distribution) follows a normal distribution, we can calculate the standard deviation, and from this same normal distribution finally choose gas limits for the “Good,” “Caution,” and “Warning” categories.

Since for a normal distribution it is true that:

the Standard Deviation, $S = IQR / 1.35$, and Mean = Median, then

$S = 1.58 / 1.35 = 1.17$

and

Mean = 2.30

Using the mean and standard deviation numbers, we have a fully defined normal distribution. This normal distribution (ND) is our final distribution, built upon the natural log values from the interquartile range of the original dataset, after the removal of outliers. Figure 10 shows this final ND, along with the previous “best fit” ND and the original distribution of natural log values (with outliers removed). Note that the final ND follows the interquartile range of the dataset very closely, as it should, as it was built upon that range of values. It does not, however, pass through most of the lower values of the dataset since, as explained earlier, many of these lower values have significant rounding error, and therefore do not follow the normal distribution.

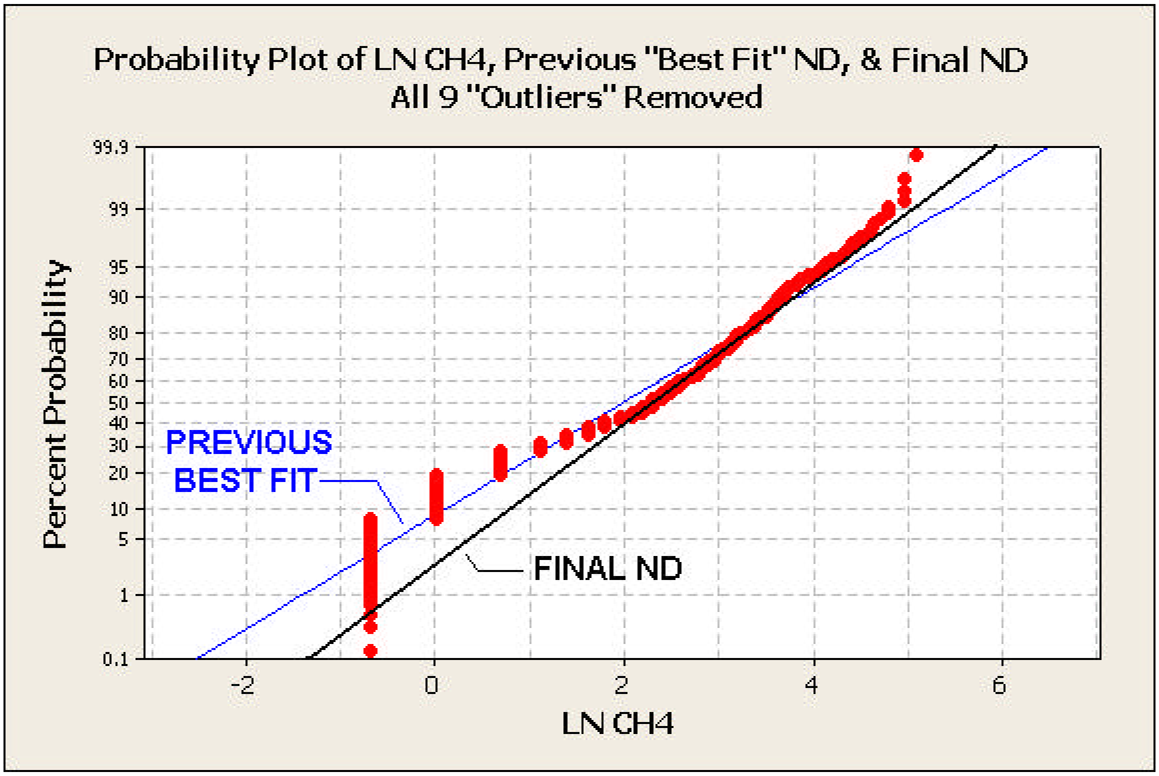

Figure 10: Probability Plot of Ln of CH4, Previous Best-Fit ND, and Final ND All 9 "Outliers" Removed

With the final normal distribution defined, the "Good," "Caution," and "Warning" gas limits for CH4 were easily calculated. The limits for each were chosen as follows:

"Good" gas limit = 90th percentile point of the normal distribution,
"Caution" gas limit = 98th percentile point of the normal distribution,
"Warning" = any gas quantity above the 98th percentile point of the normal distribution.

For a normal distribution,

the 90th percentile point, C0.90 = Mean + 1.28*S, and
the 98th percentile point, C0.98 = Mean + 2.05*S.

therefore, for our final normal distribution, with mean = 2.30 and S =1.17,

C0.90 = 2.30 + 1.28*1.17 = 3.80, and
C0.98 = 2.30 + 2.05*1.17 = 4.70

Remember that the C0.90 and C0.98 percentile points apply to the normal distribution of the natural logarithm of the original gas values. To convert these points back to gas values in ppm, we simply calculated their inverse-log, as follows:

C0.90 in ppm = exp(3.80) = 45 ppm of CH4
C0.98 in ppm = exp(4.70) = 110 ppm of CH4.

Therefore, the gas limit categories for CH4 were set as follows:

CH4 in ppm is "Good" if
    CH4 gas ≤ 45 ppm
CH4 in ppm is in the "Caution" range if
    45 ppm < CH4 gas ≤ 110 ppm
CH4 in ppm is in the "Warning" range if
    CH4 gas > 110 ppm

These gas limit values were similarly calculated for H2, C2H6, C2H4, C2H2, CO, and CO2, for both mineral oil-filled and silicone fluid-filled T/Rs.

Fault Assessment using Ratio Analysis

Once a given DGA result is assessed for each individual gas, in terms of a "Good," "Caution," or "Warning" assessment, a ratio analysis can be applied to help define the type of fault that may be occurring inside the T/R.

If all individual gasses were within their respective "Good" range, then there was no indication of a fault by this assessment method, and no review of the gas ratios would be necessary. But if one or more of the gasses were in the "Caution" or "Warning" range, indicating that an internal fault/problem may be occurring, then an examination of the gas ratios can help indicate the fault type.

The ratios examined are the classic "Rogers ratios" developed by R. R. Rogers. These are as follows:

- CH4 / H2
- C2H2 / C2H4
- C2H4 / C2H6

However, rather than using the interpretation method historically applied to these ratios, which is described in IEEE Std C57.104, instead diagnostic messages for each ratio were developed in a manner similar to that for the gas values.

Before it is considered appropriate to calculate a gas ratio, at least one of the two gasses in the ratio should be equal to or greater than 10x their respective detection limit. So, the minimum gas quantities were considered to be 10 ppm for CH4, C2H6, C2H4, and C2H2, and 30 ppm for H2. This also eliminates the problem of having a zero value in the denominator of the ratio. With this caveat in mind, the datasets of 519 DGA results for mineral oil-filled T/Rs and 340 DGA results for silicone fluid-filled T/Rs were again used to develop C0.90 and C0.98 percentile points from the distribution of values of each ratio. The method used to do this followed that of the gas limits, by transforming the ratio values into their natural log values, removing outlier values, and reconstructing a normal distribution based on the interquartile range of the filtered distribution. A summary of the final normal distributions for each ratio are shown as follows:

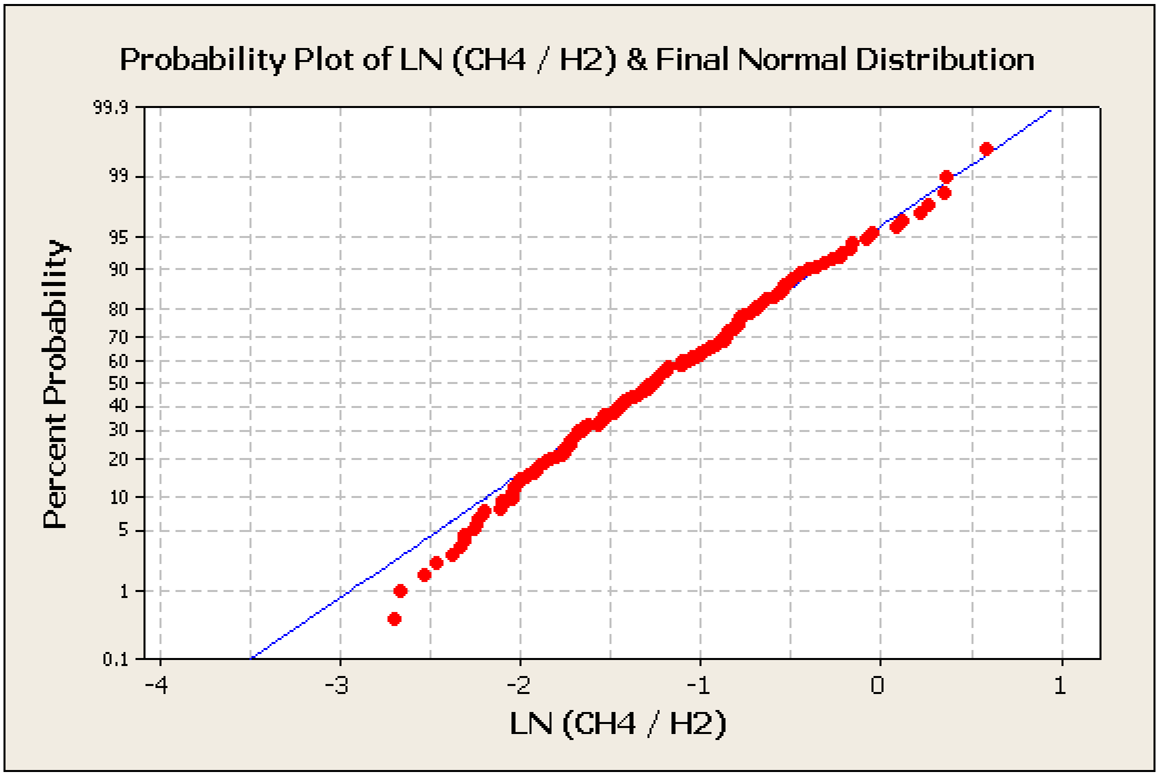

Figure 11: Probability Plot of Ln of CH4/H2 & Final Normal Distribution All "Outliers" Removed

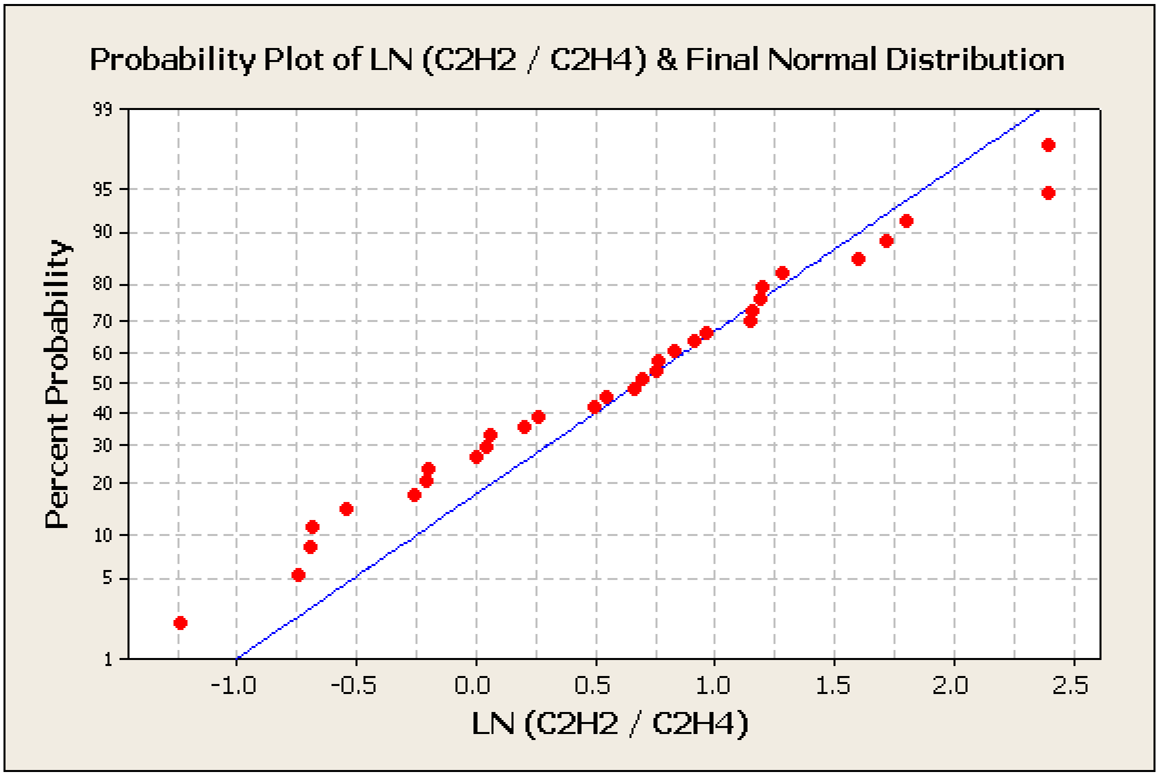

Figure 12: Probability Plot of Ln of C2H2/C2H4 & Final Normal Distribution All "Outliers" Removed

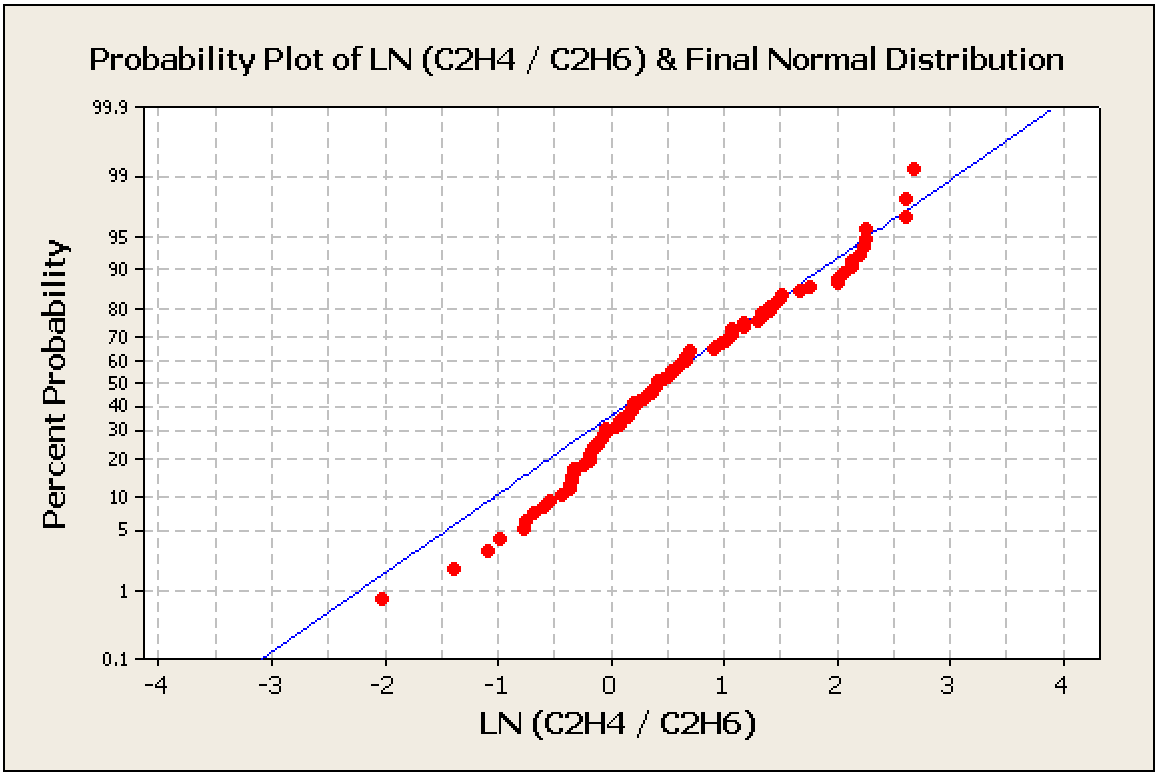

Figure 13: Probability Plot of Ln of C2H4/C2H6 & Final Normal Distribution All "Outliers" Removed

Using the “CH4 / H2” ratio as an example, the diagnostic limits, based on the final normal distribution of its natural log values, were as follows:

98th percentile point, $C_{0.98} = 1.2$
90th percentile point, $C_{0.90} = 0.7$
10th percentile point, $C_{0.10} = 0.1$
2nd percentile point, $C_{0.02} = 0.06$

The values shown above were then used as a guide for providing diagnostic messages regarding the possible fault/problem type. The diagnostic phrases for the CH4/H2 ratio are as follows:

CH4 / H2 value	Diagnostic
> 1.2	Strong indication of excessive internal heating
> 0.7, <= 1.2	Moderate indication of excessive internal heating
>= 0.06, < 0.1	Moderate indication of partial discharge activity
< 0.06	Strong indication of partial discharge activity

Diagnostic messages for the other two ratios were similarly created. Note that in the case of a DGA result with $C_2H_2 > 1$ppm, then in addition to the results of the C_2H_2/C_2H_4 ratio, there will be a diagnostic statement “Strong indication of internal arcing” appearing on a diagnostic report.

Future Work

Future work includes:

- Increasing the dataset from which the gas limits and ratio limits were calculated.
- Establish condition limits based on gassing rates.
- Compile case studies, comparing results with the condition limits presented here.

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Acknowledgment

Thank you to Mr. Jim Dukarm of Delta-X Research for his explanations of statistical methods.

Thank you to NWL Transformers, Inc. in Bordentown, NJ, and to CE Power Solutions in Lake Hamilton, FL for allowing me to tour their facilities.