Thermodynamic Estimation of Transformer Fault Severity

Fredi Jakob, *Member, IEEE*, and James J. Dukarm, *Life Member, IEEE*

***Abstract*—Conventional practice for transformer dissolved gas analysis (DGA) is to use concentrations of several fault gases, with or without total dissolved combustible gas, for evaluating apparent fault severity. We suggest a simpler approach based on the normalized energy intensity (NEI), a quantity related directly to fault energy dissipated within the transformer. DGA fault severity scoring based on NEI is shown to be sensitive to all IEC fault types and to be more responsive to shifts in the relative concentrations of the fault gases than scoring based on fault gas concentrations. Instead of eight or more gas concentration limits, NEI scoring requires only two or three limits that can be empirically derived to suit local requirements for any population of mineral-oil-filled power transformers.**

***Index Terms*—Dissolved gas analysis (DGA), enthalpy, fault energy, fault severity, normalized energy intensity (NEI), transformer.**

I. Introduction

ABNORMAL energy dissipation inside a power transformer results in partial destruction of liquid and solid insulating materials, generating trace amounts of gaseous byproducts dissolved in the oil. The most common transformer insulation liquid is a refined mineral oil. Most commonly used for solid insulation are kraft paper and pressboard made of highly processed cellulose material.

Transformer dissolved gas analysis (DGA) consists of collecting oil samples from transformers, measuring the concentrations of dissolved gases in the oil samples, and interpreting those concentrations (and any changes since previous samples). The main interpretive results are as follows:

- a determination whether there is any sign of a fault, that is, an abnormality that may be a precursor to failure;
- if there is evidence of a fault, identification of the apparent fault type;
- ranking the transformer's condition based on the absence of a fault or the apparent fault severity.

It is the third aspect of DGA—fault severity assessment—that is the subject of this paper. We are not proposing a new method of fault-type identification.

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F. Jakob is an Emeritus Professor of Chemistry at California State University, Sacramento, CA 95819 USA (e-mail: fredi.jakob@gmail.com).

J. Dukarm is with Delta-X Research Inc, Victoria, BC V8R 6T4 Canada (e-mail: j.dukarm@ieee.org).

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The principal gases that are measured and interpreted for DGA are hydrogen (H_2), the low molecular weight hydrocarbon gases methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), and acetylene (C_2H_2), and the carbon–oxide gases carbon monoxide (CO) and carbon dioxide (CO_2). Dissolved oxygen (O_2) and nitrogen (N_2) are also measured and interpreted, but they are not byproducts of insulation deterioration.

Current methods of transformer DGA fault severity classification employ statistically or empirically derived gas concentration threshold levels, usually referred to as limits, based on these principles:

1) Hydrocarbon gas produced in a transformer is the result of abnormal stress or an internal defect (fault).
2) The amount of each hydrocarbon gas produced since the transformer was known to be in good condition is roughly proportional to the intensity and duration of the abnormal condition that produced it.

Hydrogen and carbon monoxide are very useful for fault detection and diagnosis and should not be ignored for those purposes. As we discuss in Section II-A, however, hydrogen and carbon monoxide can be produced, sometimes in large amounts, by processes that are not fault related. The fact that they are not exclusively fault related complicates their usefulness for fault severity assessment.

A. IEC and IEEE Multigas DGA Severity Classification

The IEC 60599 transformer DGA guide [1] employs two limits for each combustible gas. The lower limit, called a "typical concentration value," is a threshold above which closer attention and investigation may be needed if gas concentrations are rising. The "typical value" is often chosen as the 90th percentile value of a gas concentration in a large database. The higher IEC limit for each gas, the "alarm concentration value," is set to a level where an urgent response is likely to be needed. Although the IEC guide does not prescribe numeric severity levels, for discussion purposes, the IEC scheme can be regarded as classifying DGA results into three levels, where level 1 (below the "typical value") is the normal condition; level 2 is the intermediate level, where there may or may not be evidence of an active fault; and level 3 (at or above the "alarm value") signifies increased risk of failure.

The IEEE C57.104 DGA guide for oil-filled transformers [2, Sec. 6.5] classifies gas concentrations into condition levels 1 through 4 based on three limits for each combustible gas and for total dissolved combustible gas (TDCG). IEEE condition levels 1 and 2 correspond to their IEC counterparts, while levels 3 and 4 correspond to IEC level 3.

TABLE I
HYDROGEN AND CO CONTENT OF TDCG

TDCG %-ile	Median %CO	Median %(H_2+CO)	Sample Records
(All)	57	72	76232
< 90	57	72	68852
90-95	69	82	3695
95-98	45	75	2194
≥ 98	8	27	1491

B. Total Dissolved Combustible Gas (TDCG)

While it is conventional and practical to base DGA fault severity assessment on multiple gas concentrations, especially on the four light hydrocarbon gases, it seems highly desirable to simplify that task by finding a single quantity upon which fault severity assessment can be based.

Table III of the IEEE guide [2] for DGA in oil-filled transformers advocates the use of total dissolved combustible gas (TDCG) for severity assessment, presumably on the principle that every transformer fault produces a combination of combustible gases. Unfortunately, TDCG's reliability as a fault severity indicator is questionable because hydrogen and carbon monoxide make up most of it, and production of those gases in a transformer is not exclusively fault related.

The degree to which the inclusion of H_2 and CO tends to corrupt the apparent fault severity based on TDCG is difficult to quantify, but Table I, derived from the large database of electric utility DGA data discussed in Section III, shows that those gases tend to be dominant in TDCG in all but the most extreme cases. The median proportion of CO in TDCG is 57%, while the median proportion of $H_2 + CO$ in TDCG is 72%. Only in the 2% of samples with the very highest TDCG concentrations are the exclusively fault-related gases predominant over hydrogen and CO.

Another problem with TDCG as a fault severity indicator, discussed in [3], is that it gives methane and ethane (associated with low and medium-range thermal faults) equal weight with acetylene and ethylene (associated with arcing and high-range thermal faults). As is demonstrated in [3], that tends to make TDCG relatively less responsive to the most energetic fault types.

C. Energy Weighting and NEI

In [3], we show that the sensitivity of a gas sum such as total dissolved hydrocarbon gas (TDHG) to arcing and high-range thermal faults is improved by weighting the gas concentrations in proportion to their respective enthalpies of formation from n-octane.

The *enthalpy of formation* of substance B from substance A is the amount of energy required to produce one mole of B from A, or M_B grams of B, where M_B is the molecular mass of B expressed in grams per mole. For example, the molecular mass of methane is 16.043 g/mol. A mole of a gas (such as methane) has a volume of 22.4 L at standard temperature and pressure (273 K and 101.325 kPa). As shown in Table II, the enthalpy of formation of methane gas from n-octane is 77.7 kJ/mol. For details on how the enthalpies in the table were calculated, see [3].

TABLE II
ENTHALPIES OF FORMATION OF FAULT GASES FROM N-OCTANE

Gas		Enthalpy (kJ/mol)
Methane	(CH_4)	77.7
Ethane	(C_2H_6)	93.5
Ethylene	(C_2H_4)	104.1
Hydrogen	(H_2)	128.5
Acetylene	(C_2H_2)	278.3

Source: [3] Table III

TABLE III
COMPOSITION OF THE DGA DATABASE

Source	Transformers	DGA Samples
A	3889	21053
B	6203	56403
ALL	10092	77456

TABLE IV
ESTIMATED RELATIVE UNCERTAINTIES BASED ON MODERATE-RANGE DATA

Variable	Relative Uncertainty
H_2	0.30
CH_4	0.19
C_2H_6	0.18
C_2H_4	0.16
C_2H_2	0.34
CO	0.26
TDCG	0.26
NEI	0.18

TABLE V
EMPIRICAL N_2/O_2 LIMITS FOR CLASSIFYING TRANSFORMERS AS HIGH-O_2 OR LOW-O_2

Source	N_2/O_2 Limit
A	6.85
B	5.51
All	5.94

It seems reasonable to suspect that instead of gas concentrations, the total fault energy could be a suitable basis for severity assessment. The respective concentrations and enthalapies of formation of the hydrocarbon gases can be used to calculate a quantity directly related to fault energy dissipated within the transformer, which we call the *normalized energy intensity (NEI)*. As is shown below, NEI-based fault severity assessment is sensitive to all IEC fault types and has superior responsiveness to changes in the composition of the fault gas mixture.

II. NORMALIZED ENERGY INTENSITY

Lapworth published a DGA interpretive method [4] employing empirically weighted gas concentrations for fault-type identification and severity scoring. Our 2012 paper [3] showed that natural weights—based on the energy required to produce fault gases from mineral oil—can be used for energy-weighting of sums of fault gas concentrations, improving sensitivity to high-energy fault types T3 and D2.

In fact, the enthalpies of formation shown in Table II can be used to calculate a "normalized energy intensity" NEI (kJ/kL) for fault gas concentrations found in a transformer oil sample.

The NEI based on concentrations of the four hydrocarbon gases: methane, ethane, ethylene, and acetylene is shown below to be a suitable quantity for DGA fault severity classification.

A. Rationale

Why should NEI not include carbon monoxide or dioxide? Cellulose is a labile material that decomposes spontaneously even at ambient temperatures. The rate of cellulose decomposition is directly related to temperature and other variables, such as moisture, acidity, and oxygen dissolved in the oil. Intermediate decomposition products are formed when cellulose decomposes, but the final decomposition products are carbon monoxide, carbon dioxide, and water. Production of those three compounds continues throughout the life of the cellulose-based insulation. Carbon oxides can also be generated from the oil at high temperatures if sufficient oxygen is present. For these reasons, we have not included carbon dioxide and carbon monoxide in the NEI calculations.

In contrast to cellulose, the many organic molecules found in mineral oil transformer fluids are thermodynamically stable. Since the spontaneous decomposition of those molecules at temperatures normally found in transformers is minimal, the low molecular weight hydrocarbon gases: methane, ethane, ethylene, and acetylene are almost exclusively formed by abnormal energy dissipation in the oil.

Hydrogen is also produced when oil molecules are destroyed. It is definitely a fault gas, and we considered using it in the calculation of NEI. There are, however, two problems with hydrogen as a fault severity indicator. First, hydrogen can be produced from nonfault processes, such as electrolysis of water and reaction of acidic material with galvanized metal. Hydrogen has also been observed as a source of stray gassing in hydro-refined transformer oils. The second problem is that hydrogen is a very small diatomic molecule and has a high escape velocity from mineral oil. Thus, the hydrogen concentration measured for DGA has poor reproducibility due to a loss of gas from the transformer and from fittings and syringes during oil sample collection and processing. This variability in hydrogen concentration measurements is a major source of “noise” observed with DGA data.

To summarize, we recommend inclusion of only the hydrocarbon gases methane, ethane, ethylene, and acetylene for the calculation of NEI to represent fault energy dissipated in the transformer oil.

B. Calculation

To calculate NEI, the concentration (μL/L—ppm by volume) of each hydrocarbon gas is multiplied by (1 L)/($10^6\mu$L) and then by (1 mol)/(22.4 L) to convert the numerator to moles, then multiplying by (10^3 L/kL) converts the denominator from L to kL. The resulting quantity (mol/kL) is multiplied by the enthalpy of formation (kJ/mol) to obtain kJ/kL for that gas. The sum of the kJ/kL quantities for the four hydrocarbon gases is the NEI. With some algebraic simplification, the calculation is

$$\mathrm{NEI} = \frac{77.7\mathrm{CH_4} + 93.5\mathrm{C_2H_6} + 104.1\mathrm{C_2H_4} + 278.3\mathrm{C_2H_2}}{22400} \quad (1)$$

where, in accordance with ordinary usage, $CH_4, C_2H_6, C_2H_4, C_2H_2$ denote the respective gas concentrations in μL/L.

If the gas concentrations are reported at a temperature other than 273 K (0 °C), it is necessary to multiply NEI as calculated before by the temperature correction factor $273/(273 + T)$, where T is the Celsius reporting temperature for the gas concentrations.

ASTM D3612 [5] specifies a reporting temperature of 0 °C, while IEC 60567 [6] specifies 20 °C. As indicated in [7] (Table X), various reporting temperatures are used for online DGA monitors.

III. Preliminary Statistical Analysis

DGA databases were contributed by two large U.S. electric utilities, identified here as Source A and Source B. Incomplete samples (with missing gas data) and known after-failure samples were removed. One sample per year (the latest) was retained for each transformer, to avoid bias from closely spaced investigative sampling. NEI was inserted into each sample record. The composition of the combined database is indicated by Table III.

A. Relative Uncertainty of NEI

Average relative uncertainty of NEI and TDCG was estimated directly and indirectly (by calculation from uncertainties of the relevant gas concentration measurements) from a subset of the combined database where all variables were limited to a moderate range. The lower limit of the moderate range was 1 μL/L for acetylene, 10 μL/L for other gases and TDCG, and 0.1 kJ/kLfor NEI. The upper limit of the moderate range for acetylene was 10 μL/L, and for all other gas concentrations and NEI, it was the respective 90th percentile. All of those upper limits (except for acetylene's) are the respective L_1 limits from Tables VI and VII.

The restriction to moderate ranges was motivated by two considerations. First, the uncertainties of the gas concentrations and NEI are of practical importance mainly in those ranges, characteristic of no-fault and incipient-fault conditions. Second, the range restriction eliminates most large gas increments that would interfere with the estimation of nonfault-related variation.

All of the direct statistical estimates of relative uncertainty are shown in Table IV. The high estimated uncertainty for acetylene is presumably due to the restriction to low concentrations (1–10 μL/L) where, as noted in [8], the relative uncertainty is generally high. For acetylene, concentrations above the low range are almost all fault related and, therefore, unsuitable for the determination of normal measurement uncertainty. The high estimated relative uncertainties of hydrogen and carbon monoxide are consistent with poor reproducibility due to leakage, as noted in Subsection II-A.

Indirect relative uncertainty estimates for NEI and TDCG were calculated for each sample record using the combustible gas uncertainties of Table IV and a formula for combined standard uncertainty when all measurement variables have correlation +1 (see [9, 5.2 Note 1]), since all gases tend to increase simultaneously. The mean relative uncertainty calculated in this way was 0.18 for NEI and 0.24 for TDCG.

These results indicate that the relative uncertainties of NEI and TDCG are, on average, not worse than those of the gas concentration measurements upon which they depend.

B. *Stratification by* N_2/O_2

An exploratory analysis [10] of a large transformer DGA database was conducted for IEEE/PES Transformers Committee Working Group C57.104 to investigate the effects of transformer age, megavolt-ampere rating, kilovolt rating, and oxygen/air ratio on distributions of key gas concentrations. The largest effect was associated with the proportion of dissolved oxygen versus nitrogen. Transformers with more oxygen in the oil tend to have lower concentrations of dissolved combustible gases.

The balance between oxygen and nitrogen in the transformer oil depends on the oil preservation system of the transformer. Some preservation systems—and transformers with leaky conservator diaphragms and gaskets—allow atmospheric oxygen to diffuse into the transformer, while sealed or nitrogen-regulated systems generally have very low oxygen content in the oil relative to nitrogen.

Unfortunately, the databases used for statistical derivation of gas concentration limits for DGA sometimes have incomplete, unreliable, or entirely missing information about the oil preservation types of the transformers. In such cases, it is useful to classify transformers as low oxygen or high oxygen, based on the available DGA data.

The median N_2/O_2 ratio value was calculated for each transformer, based on all of its DGA samples, and for each source and for the combined database, the distribution of those transformer median values was plotted. With a logarithmic horizontal axis, these distributions were all seen to have a local minimum probability density between $N_2/O_2 = 2$ (oil saturated with air) and $N_2/O_2 = 10$ (very low oxygen in oil). (See Fig. 1.) The location of that local minimum along the horizontal axis was used to define a limit for each source for classifying transformers as low oxygen or high oxygen. A transformer is in the high-oxygen class if its median N_2/O_2 is less than the limit; otherwise, it is in the low-oxygen class. The N_2/O_2 limits for each data source and for the combined database are shown in Table V.

The empirical N_2/O_2 limit of 5.94 for the combined database corresponds to $O_2/(N_2+O_2) = 0.14$, close to 0.15, one of the ad-hoc threshold values for $O_2/(N_2+O_2)$ used in [10].

C. *DGA Limits*

IEEE-style gas concentration limits are conventionally based on 90th and 95th percentile gas concentrations from a large database with postfailure samples removed. If a four-level severity classification is desired, a 98th or 99th percentile limit is added. For this study, we derived DGA limits for low-oxygen and high-oxygen transformers separately, using 90th, 95th, and 98th percentile gas concentrations.

Tables VI–VIII show hydrocarbon gas and NEI DGA limits for the combined database. Similar limits were calculated for the individual data sources A and B. The large difference between the low-oxygen percentile limits and the high-oxygen ones shows that separating the transformers into two oxygen-level groups for DGA interpretation is worthwhile.

Because of the very low incidence of acetylene in normally operating electric utility power transformers, the 90th and even 95th percentile acetylene concentrations in many transformer populations are zero or very close to zero, making those percentiles unsuitable for use as DGA limits. For the low-oxygen transformers in the combined database, the 90th, 95th, and 98th percentile acetylene concentrations are 0, 1, and 6 μL/L, respectively. For the purposes of this study, the acetylene limits in

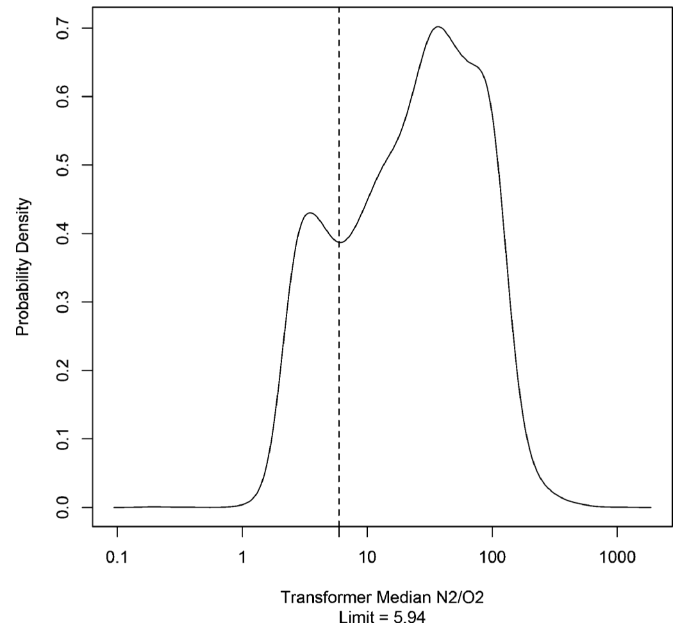

Fig. 1. Distribution of the transformer median N_2/O_2 for the combined database. The vertical dotted line marks the ratio limit value of 5.94.

TABLE VI
DGA LIMITS (μL/L) FOR HYDROCARBON GAS CONCENTRATIONS BASED ON 90TH, 95TH, AND 98TH PERCENTILES OF COMBINED DATA

Group	Gas	L_1	L_2	L_3
High-O_2	Methane	18	37	102
High-O_2	Ethane	24	56	146
High-O_2	Ethylene	43	78	179
Low-O_2	Methane	72	120	221
Low-O_2	Ethane	120	227	433
Low-O_2	Ethylene	44	91	295
All	Acetylene	2	10	36

TABLE VII
DGA LIMITS (kJ/kL) FOR NORMALIZED ENERGY INTENSITY (NEI) BASED ON 90TH, 95TH, AND 98TH PERCENTILES OF COMBINED DATA

Group	L_1	L_2	L_3
High-O_2	0.39	0.72	1.98
Low-O_2	1.02	1.87	4.00

TABLE VIII
ALTERNATIVE NEI DGA LIMITS (kJ/kL) BASED ON 80TH, 90TH, AND 95TH PERCENTILES OF COMBINED DATA

Group	L_1	L_2	L_3
High-O_2	0.20	0.39	0.72
Low-O_2	0.51	1.02	1.87

[2, Table 1] are used instead of percentile-based limits for both low-oxygen and high-oxygen transformers. Those limits, in our notation, are $L_1 = 2$, $L_2 = 10$, and $L_3 = 36$ in units of μL/L.

The NEI limits in Tables VII and VIII are based on different sets of percentiles, as the table captions indicate. The motivation for an alternative set of NEI limits is explained in Subsection V-A.

IV. DGA Scoring

The gas concentration limits are used for assigning a score, or numeric condition code, to a transformer DGA sample as a rough indicator of fault severity. As described in [1] and [2], the interpretation and ranking of DGA results for actual transformer condition assessment involves nuances that are not essential to our purpose here, which is to compare DGA scoring based on gas concentration limits versus scoring based on NEI limits, to show that NEI-based scoring is at least as sufficient for DGA fault severity assessment as gas concentration scoring.

IEEE-type numeric DGA scores are customarily whole numbers, but for better comparison of scoring methods we include a fractional part in the score by interpolation. According to common usage, a score below 2 is considered acceptable for normal operation (although, in practice, the score is not all that is taken into consideration); a score of 2 or higher motivates investigation, possible supplementary testing, and possible consideration of mitigative or corrective action. A score of at least 2 but less than 3 would usually be considered cautionary, at least 3 but less than 4 would be reacted to more urgently, and a score of 4 or more would usually be treated as an emergency or at least as a sign of advanced deterioration.

To support these interpretations and their economic consequences, the DGA limits can be and often are adjusted for site-specific conditions, requirements, and budgetary constraints. As [1] indicates, the choice of percentiles or other criteria for initial derivation of DGA limits is a matter of engineering judgment, not a normative requirement.

For comparison of severity scoring based on gas concentrations versus NEI, the combined database was augmented by classifying each transformer according to its oxygen content, selecting the appropriate set of DGA limits for each transformer, adding an HC gas score and an NEI score to each sample record based on those limits, and adding an apparent fault type to each sample record having hydrocarbon gas concentrations that were not extremely low. Details of that process were as follows.

A. Choose DGA Limits for Each Transformer

Each transformer was classified as low oxygen or high oxygen by comparing its median N_2/O_2 with the N_2/O_2 limit for its respective data source. A set of hydrocarbon gas and NEI limits was chosen based on the data source and the transformer's high/low-oxygen classification.

B. Assigning an HC Gas Score to Each Sample

For each oil sample, each of the hydrocarbon gases (methane, ethane, ethylene, acetylene) was given a score as follows, based on its reported concentration x and the limits L_1, L_2, L_3 for the gas according to the transformer's assigned DGA limits.

- If $x \geq L_3$, the gas score is 4.0.
- If $L_2 \leq x < L_3$, the gas score is $3 + (x - L_2)/(L_3 - L_2)$.
- If $L_1 \leq x < L_2$, the gas score is $2 + (x - L_1)/(L_2 - L_1)$.
- If $x < L_1$, the gas score is $1 + x/L_1$.

The maximum of the four individual gas scores was used as the HC gas score of the sample.

C. Assign the NEI Score to Each Sample

For each oil sample, the NEI was calculated from the hydrocarbon gas concentrations. Then an NEI score for the sample was obtained by comparing the NEI value x with the transformer's NEI limits L_1, L_2, L_3 according to the same four rules as given before. For NEI, there is only one score, so it is not necessary to take a maximum.

D. Assign Apparent Fault Type to Samples

For samples where at least one of methane, ethylene, or acetylene had a concentration of at least 10 μL/L, an apparent fault type was assigned, based on the Duval Triangle [11]. The assignment of an apparent fault type was done for purposes of statistical comparison, not as a judgment that any particular samples did or did not indicate a transformer fault.

Fault gases are often present in moderate amounts in trouble-free transformers due to the cumulative result of operational stress and incidents, such as temporary overloading, hot weather, and through faults. In those cases, the apparent fault type indicates the general nature of the dominant process responsible for generating the residual gases found in the transformer. See Table IX for the distributions of the apparent fault types for the combined database.

TABLE IX
Distribution of Apparent Fault Types in the Combined Database

Fault Type	Samples	%Samples	Description
PD	2488	3.21	Partial discharge
T1	12140	15.67	Thermal - below 300 °C
T2	13239	17.09	Thermal - 300 to 700 °C
T3	15144	19.55	Thermal - above 700 °C
DT	740	0.96	Thermal and arcing
D1	357	0.46	Low-energy discharge
D2	609	0.79	High-energy discharge
(none)	32739	42.27	Low HC gas levels - no FT
	77456	100.00	

V. Comparison of the Scoring Methods

For a comparison of NEI scoring with HC gas scoring, our emphasis is on the similarities and differences of how the two methods rate the severity of generic fault types, given some reasonable set of DGA limits to work from. We do not assert that the limits used here are generically useful or that the DGA scores alone are sufficient for DGA interpretation in a production setting. The following discussion is intended to show that NEI scoring, with an appropriate choice of limits, is an adequate and effective alternative to HC gas scoring or any similar method of fault severity assessment based on gas concentrations.

TABLE X
SCORING METHOD SENSITIVITIES BY FAULT TYPE

Scoring	FT	p(2.0)	p(3.0)	p(3.95)
HC	ALL	0.20	0.10	0.04
HC	PD	0.16	0.10	0.07
HC	T1	0.30	0.15	0.05
HC	T2	0.24	0.11	0.05
HC	T3	0.41	0.21	0.09
HC	DT	0.67	0.26	0.11
HC	D1	0.98	0.77	0.41
HC	D2	1.00	0.85	0.55
NEI	ALL	0.09	0.05	0.02
NEI	PD	0.08	0.05	0.03
NEI	T1	0.17	0.06	0.01
NEI	T2	0.15	0.07	0.02
NEI	T3	0.16	0.10	0.06
NEI	DT	0.16	0.08	0.05
NEI	D1	0.20	0.12	0.10
NEI	D2	0.45	0.33	0.24
NEI*	ALL	0.18	0.09	0.05
NEI*	PD	0.14	0.08	0.05
NEI*	T1	0.35	0.17	0.07
NEI*	T2	0.34	0.15	0.07
NEI*	T3	0.29	0.16	0.10
NEI*	DT	0.30	0.16	0.09
NEI*	D1	0.47	0.20	0.13
NEI*	D2	0.65	0.45	0.33

A. *Sensitivity*

Table X shows how each scoring method, with the DGA limits from Tables VI, VII, and VIII, rates apparent fault severity. Each fault type is examined individually to see whether there are fault-type-specific differences in sensitivity, and, if so, whether they might affect the usefulness of a severity scoring method.

Each row of the table shows the sensitivity of a scoring method to a fault type at three severity levels. Here, ALL designates all of the sample records, regardless of fault type. For the three levels $s = 2.0$, 3.0, 3.95, a proportion $p(s)$ is given, which is the proportion of all sample records with that fault type that have a score greater than s according to the designated scoring method. The top level considered is 3.95 instead of 4.0 because, according to the scoring rules (Subsection IV-B), there cannot be any samples with a score greater than 4.0.

1) HC Gas Method Sensitivity: For the HC gas method and fault type ALL, meaning all 77 456 of the sample records according to Table IX, p(2.0) is 0.20. That means that 20% of all sample records have an HC gas score greater than 2.0. For the 15144-record subset with an apparent fault type of T3, 0.41 or 41% of those samples have an HC gas score greater than 2.0. For the 609-record subset with an apparent fault type of D2, practically 100% of those records have an HC gas score higher than 2.0.

For all of the fault types (DT, D1, D2) that necessarily involve a nonzero acetylene concentration, the HC gas sensitivities—particularly at the $s = 2.0$ level—are extremely high. That is because the IEEE limits for acetylene are set very low, so that almost every sample matching a DT, D1, or D2 fault type has an acetylene concentration exceeding the acetylene L_1 limit.

2) Initial Comparison of HC Gas and NEI Sensitivities: The NEI rows in Table X are for NEI scoring based on the limits defined by the 90th, 95th, and 98th percentiles of NEI. Those limits for the combined database are shown in Table VII. With those limits, NEI scoring is much less sensitive than the HC gas method at all three levels (2.0, 3.0, 3.5) to all fault types. For example, NEI, with those limits, scores 16% of T3 samples higher than 2.0, while HC gas scores 41% of them higher than 2.0. To adjust the NEI sensitivity, different limits are needed.

3) Increasing NEI Sensitivity—New Limits: Note that the ALL row for the NEI method contains proportions that are closely related to the percentiles used for defining the limit corresponding to each level. For example

$$p(2.0) = 0.09 \approx 1 - 0.90$$
$$p(3.0) = 0.05 = 1 - 0.95$$
$$p(3.5) = 0.02 = 1 - 0.98.$$

This is to be expected—if the 90th percentile of NEI defines the L_1 limit, then approximately 90% of all samples must have a score that is less than or equal to 2.0, and approximately 10% of all samples must have a score above 2.0. The split is not exact because of the effect of numerous samples sharing the same NEI value at low levels. In order to achieve NEI sensitivity similar to that of the HC gas method, then, it should suffice to define new NEI limits with percentiles corresponding in the same way to the values (0.20, 0.10, 0.04) in the ALL row of the HC gas method, that is, the 80th, 90th, and 95th percentiles of NEI. The NEI limits defined in that way are shown in Table VIII, and the corresponding sensitivity results are shown in the NEI* rows of Table X.

With the alternative NEI limits, the sensitivity of the NEI method is similar to that of the HC gas method for all fault types not involving acetylene. Scanning down the NEI* rows of Table X visually, it is evident that the NEI sensitivity is higher for the more energetic thermal fault type T3 (very hot thermal), and still higher for D1 (low-energy sparking) and D2 (high-energy arcing). That is a direct consequence of the high enthalpies of the primary indicator gases for those fault types—ethylene and acetylene (see Table II). The lower sensitivity to the less dangerous fault types—PD, T1, and T2—reflects the lower enthalpies of methane and ethane—higher concentrations of those gases are required to raise NEI to exceed an NEI limit.

Because of the high enthalpy of acetylene, the NEI scoring for arcing faults D1 and D2 is very conservative, giving, for example, 65% of all D2 samples a score higher than 2.0. In cases where a proactive response to trace amounts of acetylene is mandated, the equipment operator is free to apply special measures based on the appearance of small amounts of acetylene, regardless of the NEI score. That score, however, provides a direct indication of the level of energy dissipated so far by the fault.

B. *Rigidity*

Among samples with any particular HC gas score, many of the NEI scores will be higher and many lower (assuming that the alternative NEI limits are used). That is because in almost all cases, the HC gas score is determined by the concentration

TABLE XI
EXAMPLE—TWO SAMPLES WITH THE SAME HC GAS SCORE BUT DIFFERENT NEI SCORES

	Sample A	Sample B
Methane	10	90
Ethane	10	190
Ethylene	100	100
Acetylene	0	9
NEI	0.541	1.682
Fault Type	T3	T3
HC Gas Score	3.04	3.04
NEI Score	2.06	3.78

TABLE XII
DOMINANT GASES FOR HC GAS SCORING OF EACH FAULT TYPE

Fault Type	Key Gas	Samples	%Samples
PD	Methane	339	85.4
T1	Methane	1843	50.4
T1	Ethane	1942	53.1
T2	Ethane	2187	66.3
T3	Ethylene	5695	89.7
DT	Acetylene	580	95.6
D1	Acetylene	355	99.4
D2	Acetylene	609	100.0

of a single "key" gas, while the NEI score is based on the concentrations of all hydrocarbon gases in each case. For example, consider the two hypothetical samples from a low-oxygen transformer shown in Table XI. The NEI scores are based on the alternative limits in Table VIII. Based on 100 ppm of ethylene, both samples receive an HC gas score of 3.04. But Sample A, with very low levels of hydrocarbon gases other than ethylene, has an NEI score of 2.06, while Sample B, with much higher levels of nonethylene hydrocarbon gases, has an NEI score of 3.78. The NEI scoring method is able to distinguish between two samples that clearly represent different levels of fault activity, while the HC gas score, representing only the maximum of four individual gas concentration scores, makes no distinction.

Table XII identifies the predominant or "key" hydrocarbon gas or gases, according to the HC gas scoring method, for each fault type. The calculations for that table were based on all sample records from the combined database where the HC gas score is at least 2.0 and where a fault type is given. For brevity, let those be called "fault samples." The table shows the number ("Samples") and percentage ("%Samples") of fault samples of the indicated fault type where the score of the indicated gas is equal to the HC gas score of the sample. For each fault type, the gases that are not listed are dominant in only a small minority of cases.

Thus, for example, for fault type T3, there are 5695 fault samples where the ethylene score is equal to the sample's HC gas score. Those 5695 records represent 89.7% of all fault samples having a fault type of T3.

In summary, for the HC gas method, almost all of the PD scores are determined by methane; for T1, almost all scores are determined by methane or ethane; for T2, ethane determines most of the scores; for T3, ethylene almost always determines the score; and for DT and the arcing faults, acetylene almost always determines the score.

TABLE XIII
EXAMPLE—DGA HISTORY OF A FAILED TRANSFORMER

Sample No.	1	2	3	4	5
Days	0	1748	2170	2483	2563
Hydrogen	0	0	0	33	111
Methane	0	35	99	162	275
Ethane	0	38	75	88	128
Ethylene	0	64	169	277	451
Acetylene	0	0	0	0	56
CO	0	4	7	5	40
CO_2	57	996	1185	1437	1403
TDCG	0	141	350	565	1061
Oxygen	12456	326	1800	1200	263
Nitrogen	66326	86823	64715	73327	71006
NEI	0.000	0.577	1.442	2.217	4.280
Fault Type	(none)	T3	T3	T3	T3
NEI Score	**1.00**	**2.12**	**3.50**	**4.00**	**4.00**
HC Gas Score	1.00	2.43	3.38	3.91	4.00

VI. DGA CASE HISTORY EXAMPLE

A case history of a 90-MVA nitrogen-blanketed 138/69 kV transformer illustrates the application of NEI scoring. Data for this example are shown in Table XIII. The low-oxygen alternative NEI limits in Table VIII are used. HC gas scores, based on the low-oxygen gas concentration limits in Table VI, are provided for comparison.

Oil sample 1 contained no detectable amounts of combustible gas. About five years (1748 days) later, the methane, ethane, and ethylene levels, consistent with a T3 (high-range thermal) fault type, raised the NEI to 0.577 with a score of 2.12. That would have been sufficient to motivate investigative sampling to determine whether the transformer was still generating combustible gases. In this case, no extra sampling was undertaken.

In sample 3, a little over a year later, the hydrocarbon gas concentrations had more than doubled, raising NEI to 1.442 and the NEI score to 3.50. The large relative increase in NEI and the high score resulting from that, with an apparent fault type of T3, could be understood as an indication of an increasingly severe problem with the potential to fail the transformer.

Sample 4, about ten months later, witnessed a further large increase in methane and ethylene that increased NEI by about 50% and raised the NEI score to the "alarm" level of 4.0. Eighty days later, sample 5 revealed a very large increase of NEI by 93%, still consistent with a T3 fault, although the sudden appearance of hydrogen and a very substantial amount of acetylene suggest that there may have been some sparking or arcing. The accelerated rate of increase of NEI suggests a runaway condition. The transformer was removed from service six days after Sample 5. The failure was due to a turn-to-turn short in the high-voltage winding. Levels of CO and CO_2 remained low (for those gases) throughout the transformer's history, so there were no grounds for suspecting involvement of paper winding insulation in the fault.

VII. CONCLUSION

For transformer DGA, the assessment of relative risk or fault severity is conventionally based on the consideration of a combination of combustible gas concentrations. A model of that approach, based on concentrations of transformer oil of light hydrocarbon gases (the HC gas method), was compared with a proposed new approach, based on the fault energy required to produce the observed hydrocarbon gas concentrations (NEI).

The HC gas scoring method, and similar schemes based on different assortments of gases, require two or three gas concentration limits per gas. The scores, based on gas concentrations as proxies for fault severity, are not straightforwardly interpretable in terms of fault energy and do not discriminate between different mixtures of gas produced by more or less severe or prolonged faults. Since percentile-based gas concentration limits are usually unsuitable for acetylene, gas concentration scoring methods are forced to use precautionary acetylene limits, based on engineering judgment, which tend to rate arcing-type faults very differently than others.

The NEI DGA scoring method, based on hydrocarbon fault gas concentrations and enthalpies of formation, provides a numeric fault severity score that is directly related to the amount of fault energy expended in the oil, even for arcing-type faults. Since NEI is based on all hydrocarbon gas concentrations, not just on one at a time, it responds better to gradual increases in fault severity. It is sensitive to each of the IEC transformer fault types, and its overall sensitivity can be adjusted with a predictable effect by modifying the limits. For an IEEE-style scale of DGA scores from 1 to 4, only three NEI limits are needed. The NEI is easily calculated and, with only two or three limits to consider, the scoring logic is very simple.

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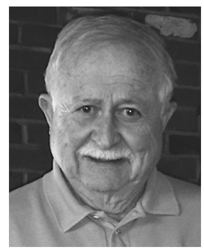
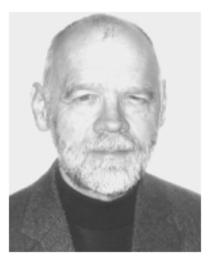


Fredi Jakob (M'10) received the B.S. degree in chemistry from the City College of New York, New York, USA, and the Ph.D. degree in analytical chemistry from Rutgers University, New Brunswick, NJ, USA.

He conducts training seminars as a Consultant for Weidmann Diagnostic Solutions Inc., St. Johnsbury, VT, USA. He was an Instructor for the previous courses offered by the Weidmann Education Division and authored many published articles. He is a Traveling Lecturer to private and governmental agencies and has been invited to speak at many electrical industry conferences, meetings, and symposia. Prior to his work with Weidmann, he was the Founder and Laboratory Director of Analytical ChemTech International Inc. (ACTI). He served as Professor of Analytical Chemistry, California State University, Sacramento, CA, USA, for 36 years. He was also a Visiting Professor at several universities in the U.S. and abroad and was a Visiting Scientist at Lawrence Laboratories at the University of California, at both Berkeley and Livermore.



James J. Dukarm (M'82–LM'15) received the M.S. degree in mathematics from St. Mary's University, San Antonio TX, USA, and the Ph.D. degree in mathematics from Simon Fraser University, Burnaby, BC, Canada.

He is the Founder and CTO of Delta-X Research Inc., Victoria, BC, Canada. He has worked full-time in the electric power industry since 1988, developing products for equipment monitoring and diagnosis, including widely used applications for factory switchgear monitoring, insulation power factor testing, and dissolved-gas analysis. Earlier, he taught mathematics and computer science at the University of Victoria, Victoria, BC, Canada, and at several BC colleges. He left academia to conduct robotics R&D in private industry.

Dr. Dukarm is a member of the IEEE Power and Energy Society and CIGRE. He is actively involved in IEEE Transformers Committee standards development.