Envirotemp® FR3® Fluid

Dissolved Gas Guide

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Dissolved Gas Analysis and Envirotemp® FR3® Fluid

What is dissolved gas analysis?

Dissolved gas analysis (DGA) is a diagnostic technique useful in preventive maintenance, condition assessment, and fault identification of liquid-filled transformers (the transformer equivalent of getting a blood test as part of a routine physical examination). The analysis determines the amounts of gases dissolved in the oil: hydrogen, hydrocarbon gases (methane, ethane, ethylene, acetylene, and sometimes propane, propylene, n-butane, and isobutane), carbon oxides (carbon monoxide and dioxide), oxygen, and nitrogen.

Why is it useful?

The types of gases dissolved in the oil, along with their amounts, relative proportions, and changes over time give us clues about what's happening in the transformer.

Where do the gases come from?

Gases are formed during normal aging processes, thermal breakdown, operation of fuses or switches, by electrical defects, or during abnormal events.

- The gases formed during oil decomposition are typically hydrogen and hydrocarbon gases.
- The gases formed from paper insulation (cellulose) decomposition are typically hydrogen, carbon oxides, and methane.
- Different types of faults generate gases with their own characteristic "signature" gas proportions.

How are the results used?

The gas analysis tells us the amounts of gases dissolved in the oil. Although all of the gas data are informative, the dissolved combustible gases are the most useful for fault diagnosis. Guides to aid in the interpretation of dissolved gases use several methods to extract information about transformer condition. The amounts, proportions, and rates of gas generation are used to help determine if a fault exists and identify the type of fault.

More important than data from a single gas sample are the rates of gas generation (how the gases change over time). The effort expended in interpreting and acting on the gas data is almost always in direct proportion to the generation rate.

How reliable is the interpretation of gas data?

Although some faults can be consistently diagnosed using DGA (active arcing faults, for example), many times evaluating the data requires the operational, maintenance, and test histories of the transformer. Even then, the interpretation may not be clear-cut. The Limitations section of the IEEE gas guide [1] sums it up this way:

> *"However, it must be recognized that analysis of these gases and interpretation of their significance is at this time not a science, but an art subject to variability."*

Where can I find a clear concise primer on DGA?

Excellent discussions of dissolved gas theory and its practical application can be found in the Facilities Instructions, Standards, and Techniques manuals published by the U.S. Bureau of Reclamation [2,3].

Can DGA be used with Envirotemp FR3 fluid?

We reach at last the heart of the matter. The short answer is YES.

Introduction

Dissolved gas data from thousands of normally operating and faulted mineral oil transformers, collected, examined, and pondered over the course of decades, form the empirical basis of a means to help assess the condition of a particular transformer. The IEEE, IEC, and U.S. Bureau of Reclamation publish guides to aid in interpreting dissolved gas data for fault diagnosis [1-4]. Because transformers using natural esters such as Envirotemp FR3 fluid are a recent development, the opportunities to evaluate actual faulted transformers are slow in coming. The few available to us, together with data from normally operating transformers and a variety of laboratory studies, have helped to validate the application of DGA to Envirotemp FR3 fluid.

Summary

Samples of Envirotemp FR3 fluid for dissolved gas determinations are taken and analyzed using the same procedures and techniques as those used for mineral oil [5-7]. The data are interpreted in much the same way as for gases in mineral oil. The combustible gases generated by faults in natural ester fluids are similar to those in mineral oil: high levels of hydrogen may be an indication that partial discharge is occurring; carbon oxides in certain ratios suggest overheated paper; hydrocarbon gases could result from a thermal fault in oil; acetylene points to arcing. Always, the first step is to determine if a fault exists using the amounts and generation rates of dissolved gases before trying to further interpret the gas data. The most useful approaches to dissolved gases in Envirotemp FR3 fluid use the gas generation rates combined with the IEEE Key Gases method or the IEC Duval method.

Differences from Mineral Oil

Gas Solubility

The solubility of gases in Envirotemp FR3 fluid differs slightly from their solubility in mineral oil (Table 1). The volume of gases generated by some faults, most notably arcing faults, can also be different. Low current arcing faults in Envirotemp FR3 fluid generate smaller volumes of gas (tests yield gas volumes of about 75% the volume generated in mineral oil). These differences might affect the utility of some ratio analysis methods and estimates of combustible gas content in the headspace.

Table 1. Gas solubility (Ostwald) coefficients for Envirotemp FR3 fluid and mineral oil

	25°C		70°C	
Gas	Envirotemp FR3 fluid [8]	mineral oil [1]	Envirotemp FR3 fluid [8]	mineral oil [8]
Hydrogen H_2	0.05	0.05	0.097	0.092
Oxygen O_2	0.15	0.17	0.255	0.208
Nitrogen N_2	0.07	0.09	0.141	0.127
Carbon monoxide CO	0.09	0.12	0.148	0.143
Carbon dioxide CO_2	1.33	1.08	1.187	0.921
Methane CH_4	0.30	0.43	0.387	0.432
Ethane C_2H_6	1.45	2.40	1.677	2.022
Ethylene C_2H_4	1.19	1.70	1.389	1.419
Acetylene C_2H_2	1.63	1.20	1.763	0.992
Propane C_3H_8	-	-	4.041	6.844
Propylene C_3H_6	-	-	4.078	5.369

Ethane and Hydrogen

Many (but not all) otherwise normally operating transformers using Envirotemp FR3 fluid have higher ethane content than their mineral oil counterparts. Other hydrocarbon gases remain low – only ethane is elevated. Occasionally, an unvarying but slightly elevated level of hydrogen is found in otherwise normally operating Envirotemp FR3 transformers. This may incorrectly indicate a partial discharge fault. These anomalies require additional study in order to suitably explain them.

Acetylene

Throughout the adaptation of gas chromatography and analysis for Envirotemp FR3 fluid, we often see a peak (identity unknown) with an elution time close to the elution time of acetylene. At times this peak is no more than a baseline rise that quickly levels off and can easily be distinguished from acetylene (Fig. 1a). In other cases, the peak appears to be genuine (more than a baseline rise) and elutes so closely to acetylene that it can be mistaken for acetylene (Fig. 1b). Because the presence of small quantities of acetylene prompts additional transformer scrutiny, the chromatographer should be aware of the possible occurrence of the misleading peak. More work must be done to identify this substance and develop criteria to reliably distinguish it from acetylene.

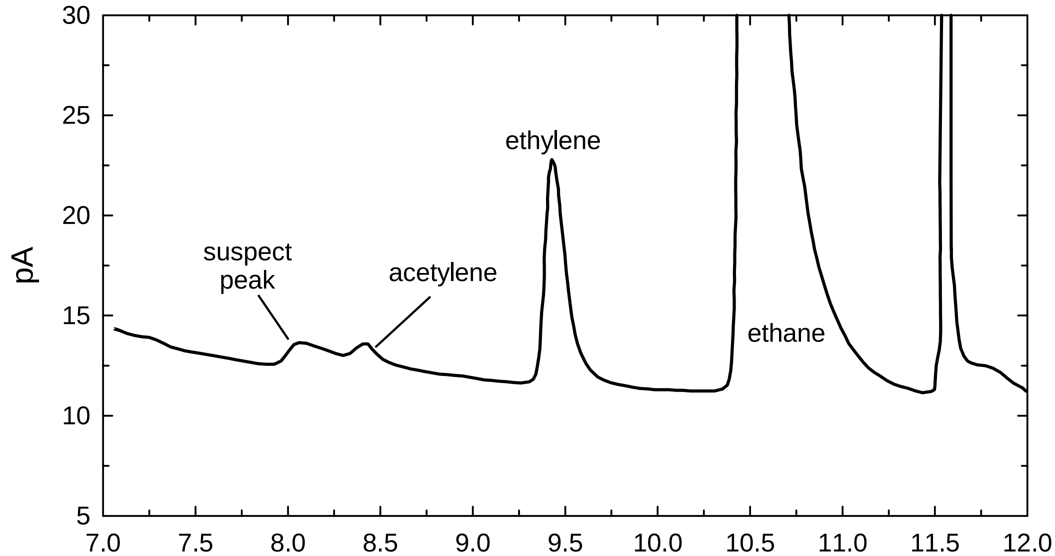


Figure 1a. Chromatogram showing a small “false acetylene” peak eluting just prior to acetylene

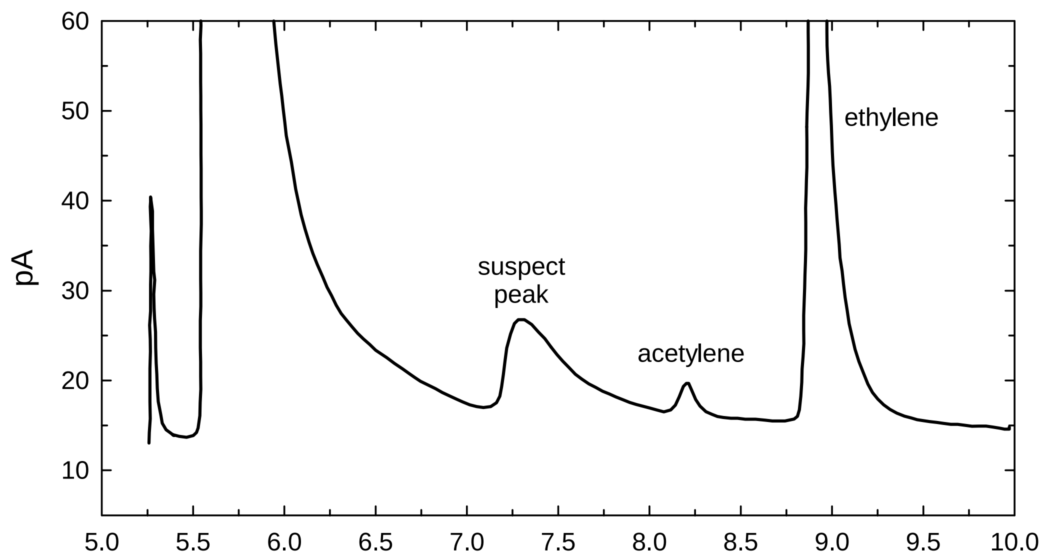


Figure 1b. Chromatogram showing a larger “false acetylene” peak that could be mistaken for acetylene

IEEE Methods of Interpretation

The IEEE gas guide [1] was written with large mineral oil transformers in mind. Applying the IEEE methods to distribution transformers can require some deviation from the guide: switches and fuses generate gases during their normal operation; the proportions and amounts of paper and oil differ from large transformers; smaller volumes of oil result in higher concentrations of gas; the lower voltages used in distribution are less likely to cause partial discharge.

Table 2 shows the gases generated by fault type from the IEEE gas guide for mineral oil. Table 3 gives the IEEE methods of interpreting the mineral oil gas data and their applicability to Envirotemp FR3 fluid. A prerequisite to applying the interpretation methods must be to determine if a fault exists using the amounts and generation rates. IEEE divides the gas generation rate into three ranges: <10 ppm/day, 10-30 ppm/day, and >30 ppm/day. The gassing rate is used in conjunction with the amount of gas present (condition method) to advise actions.

Table 2. Gases by fault type from IEEE gas guide

Fault Type			Gases Created
Thermal	mineral oil:		
		low temperature	hydrogen, methane; trace levels of ethane, ethylene
		modest temperature	hydrogen > methane; ethane, ethylene
		high temperature	hydrogen, ethylene; trace levels of acetylene
	paper		carbon monoxide, carbon dioxide
Electrical		low intensity discharges	hydrogen, decreasing quantity of methane, trace acetylene
		high intensity arcing	acetylene

Table 3. Methods of analysis from IEEE gas guide

Method	Analysis	Application to Envirotemp FR3 fluid
Condition	amounts of combustible gases	of use, but limits for ethane, carbon oxides and hydrogen may be low (limits can be low for distribution transformers in general)
Ratio		
Rogers	combinations of various hydrogen and hydrocarbon ratios	unreliable
Doerenburg	combinations of various hydrogen and hydrocarbon ratios	often not applicable; agrees with IEC Duval method when it does apply
CO_2/CO	carbon oxides ratio	applicable
Key Gases	proportions of combustible gases	applicable; FR3 fluid proportions differ slightly from those of mineral oil, and typically have a higher relative proportion of ethane

IEC Methods of Interpretation

The IEC gas guide [4] basic ratio and simplified ratio methods use various ratios of hydrogen and hydrocarbon gases to help identify fault types. The IEC Duval method looks at the relative proportions methane, ethylene, and acetylene to identify the type of fault, assuming one is present. The Duval method plots the data on a ternary graph divided into areas of fault types. This has so far been the most reliable fault identification method for Envirotemp FR3 fluid.

As with the IEEE guide, the user must determine if a fault condition exists for the interpretation methods to be meaningful. The user establishes the presence of a fault using the gas generation rate and typical gas levels of normally operating transformers. Duval reviews the IEC methods development and application [9,10].

Rates of gas increase

According to the IEC guide, an increase in gas concentrations of more than 10% per month above typical concentration values is generally considered a prerequisite for pronouncing the fault as active, provided it is clear that the precision of DGA values is better than 10% after one month. Much higher rates of gas increase, such as 50% per week, and/or evolving towards faults of higher energy (e.g. D2 or T3), are generally considered very serious, especially if they exceed alarm concentration values. In the case of power transformers, typical rates of gas productions in milliliters per day are also reported (see table A.3). Special attention should be given to cases where there is acceleration in the rate of gas increase.

IEC uses broad classes of detectable faults: partial discharge, low or high-energy discharges, and thermal faults in oil and/or paper. The basic and Duval methods subdivide these into more specific types. The simplified method identifies only the main fault type.

Table 4. Methods of analysis from IEC gas guide

Method	Analysis	Application to Envirotemp FR3 fluid
Duval	proportions of methane, ethylene, and acetylene	applicable (most reliable method overall)
Basic Ratios	combinations of methane/hydrogen, ethylene/ethane, and acetylene/ethylene ratios	applicable
Simplified Ratios	ratios of methane/hydrogen, ethylene/ethane, and acetylene/ethylene	applicable
CO_2/CO	carbon oxides ratio	applicable

Conclusions

Laboratory determinations of the types and amounts of gases generated in Envirotemp FR3 fluid as well as their absorption characteristics, viewed along with the present field data, confirm that the IEEE key gases and condition methods and the IEC methods can aid in identifying fault types in transformers filled with Envirotemp FR3 fluid. The IEC Duval method has so far been the most reliable. Both the IEEE and IEC gas guides require that a fault actually exists before applying the interpretation methods. The amounts of dissolved gases and the gassing rates in Envirotemp FR3 fluid are utilized to help determine if an active fault exists in the same way as for mineral oil.

Examples

Perhaps the best way to get a feel for DGA of Envirotemp FR3 fluid is to look at some examples. Gas data from several faulted transformers, normally operating transformers, and laboratory trials follow.

In-Service Transformers with Faults

A. factory fault
B. lightning strike
C. no-load tap changer switch – coked contacts (retrofill)

Normally Operating Transformers

D. retrofilled pad mount
E. new pad mount #1
F. new pad mount #2

Engineering and Laboratory Studies

G. regulator operational life

References

[1] "IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers", IEEE Std. C57.104-1991, Institute of Electrical and Electronics Engineers, New York, USA (http://www.ieee.org)

[2] "Transformer Maintenance", Facilities Instructions, Standards, and Techniques, Vol. 3-30, pp. 35-53, Hydroelectric Research and Technical Services Group, Bureau of Reclamation, U.S. Dept. of Interior, Denver, CO, October 2000 (http://www.usbr.gov/power/data/fist_pub.html)

[3] "Transformer Diagnostics", Facilities Instructions, Standards, and Techniques, Vol. 3-31, pp. 5-13, Hydroelectric Research and Technical Services Group, Bureau of Reclamation, U.S. Dept. of Interior, Denver, CO, June 2003 (http://www.usbr.gov/power/data/fist_pub.html)

[4] "Mineral oil-impregnated electrical equipment in service – Guide to the interpretation of dissolved and free gases analysis", IEC Standard 60599, Edition 2.0, 1999-03, International Electrotechnical Commission, Geneva, Switzerland (http://www.iec.ch)

[5] "Standard Practice for Sampling Insulating Liquids for Gas Analysis and Determination of Water Content", D3613, ASTM International, West Conshohocken, USA (http://www.astm.org)

[6] "Oil-filled electrical equipment - Sampling of gases and of oil for analysis of free and dissolved gases - Guidance", IEC Standard 60567, Edition 3.0, 2005-06, International Electrotechnical Commission, Geneva, Switzerland (http://www.iec.ch)

[7] "Standard Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography", D3612, ASTM International, West Conshohocken, USA (http://www.astm.org)

[8] Jalbert, J., Gilbert, R., Tétreault, P., El Khakani, M.A., "Matrix Effects Affecting the Indirect Calibration of the Static Headspace-Gas Chromatographic Method Used for Dissolved Gas Analysis in Dielectric Liquids", Analytical Chemistry, Vol. 75, No. 19, October 1, 2003

[9] Duval, M., "Interpretation of Gas-In-Oil Analysis Using New IEC Publication 60599 and IEC TC 10 Databases", IEEE Electrical Insulation, Vol. 17, No. 2, March/April 2001, pp. 31-41

[10] Duval, M., "A Review of Faults Detectable by Gas-in-Oil Analysis in Transformers", IEEE Electrical Insulation, Vol. 18, No. 3, May/June 2002, pp. 8-17

Example A

Transformer faulted from the factory

A new mineral oil-filled substation transformer (1.5MVA, 13.2kV-480V) showed a rapid increase in gas levels soon after installation (Figures A1, A2). After twice verifying the results, the customer re-processed the mineral oil to reduce the gas levels. This did not correct the fault as demonstrated by the subsequent gas generation rate (Figure A3). The transformer was drained and refilled with Envirotemp FR3 fluid (in hopes, perhaps, that Envirotemp FR3 fluid would heal the defect). The initially clean FR3 fluid developed the same hydrocarbon gas signature and high amounts seen in the mineral oil (Figures A4, A5). Figure A6 shows the IEEE "key gases" proportions and shows the same fault gas signature for both mineral oil and Envirotemp FR3 fluid. Figure A7 shows the IEC ternary (Duval) plot. Again, the same fault type is indicated for both. Results from other methods are shown in Tables A1 (IEEE) and A2 (IEC). An autopsy of the transformer discovered a 7.5 inch piece of metal banding steel inside the coil window of the B phase coil, causing a hole to burn through the 90-mil window insulation.

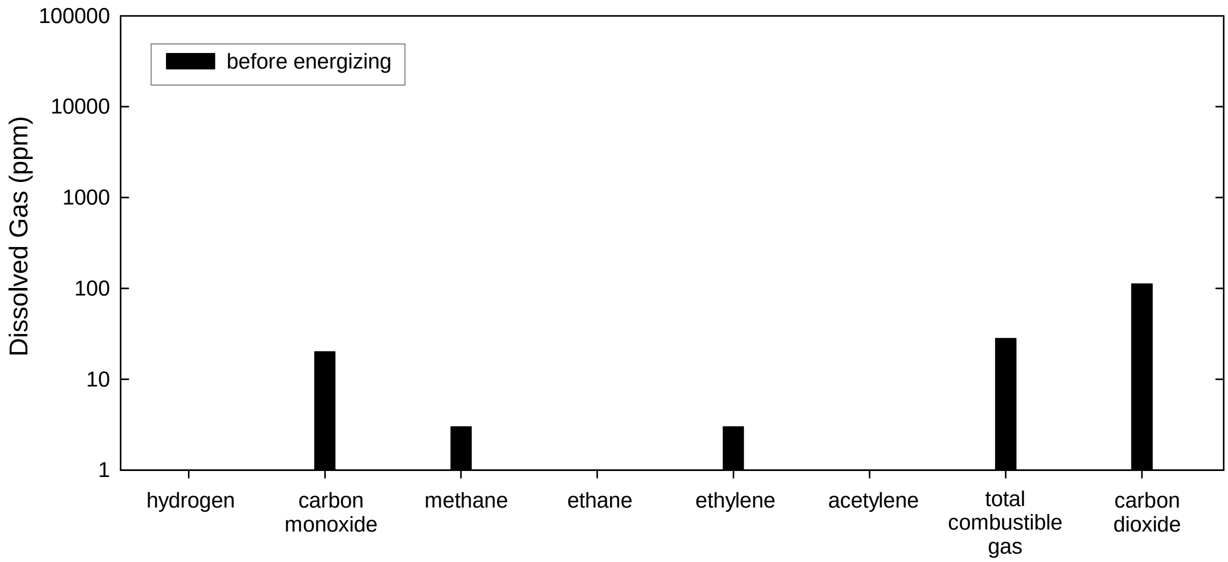


FIGURE A1. Mineral oil dissolved gas levels prior to energizing the transformer.

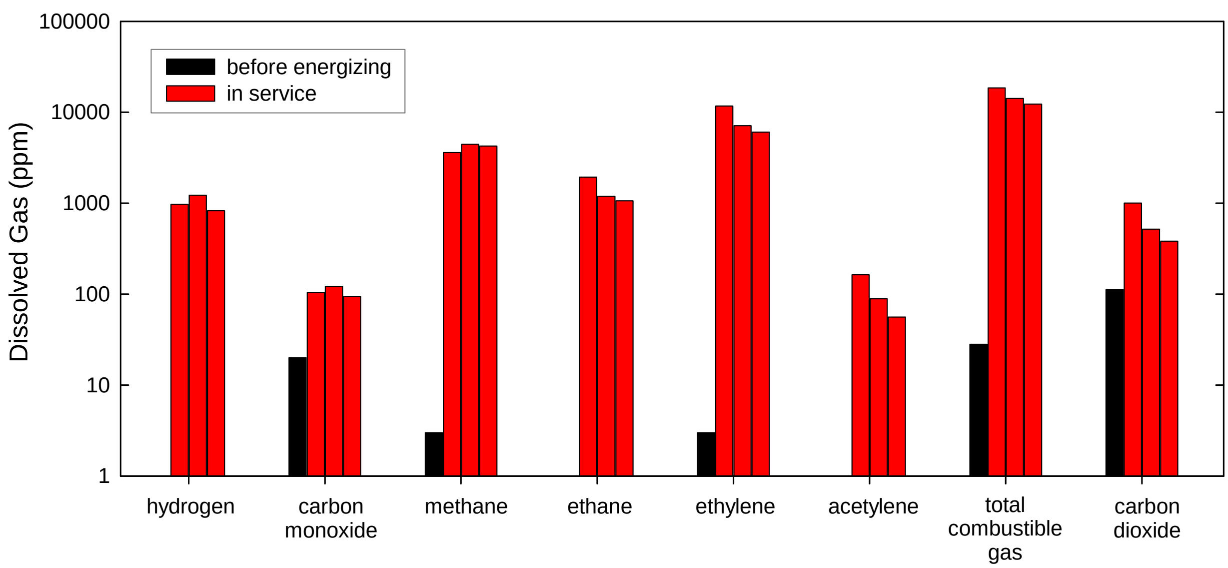


FIGURE A2. Gas levels after 7, 8, and 9 months in service (red bars) indicate a thermal fault in the mineral oil.

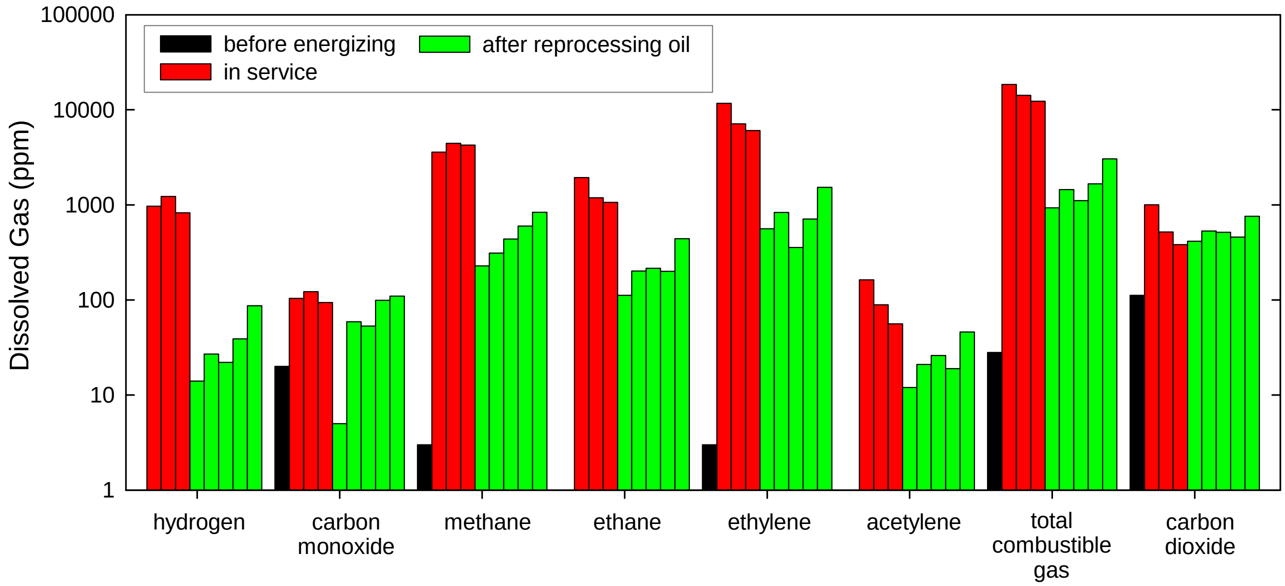


FIGURE A3. Gas levels after re-processing the mineral (green bars) oil show an initial decline due to degassing the oil, but significant gassing rates post-processing indicate an active fault.

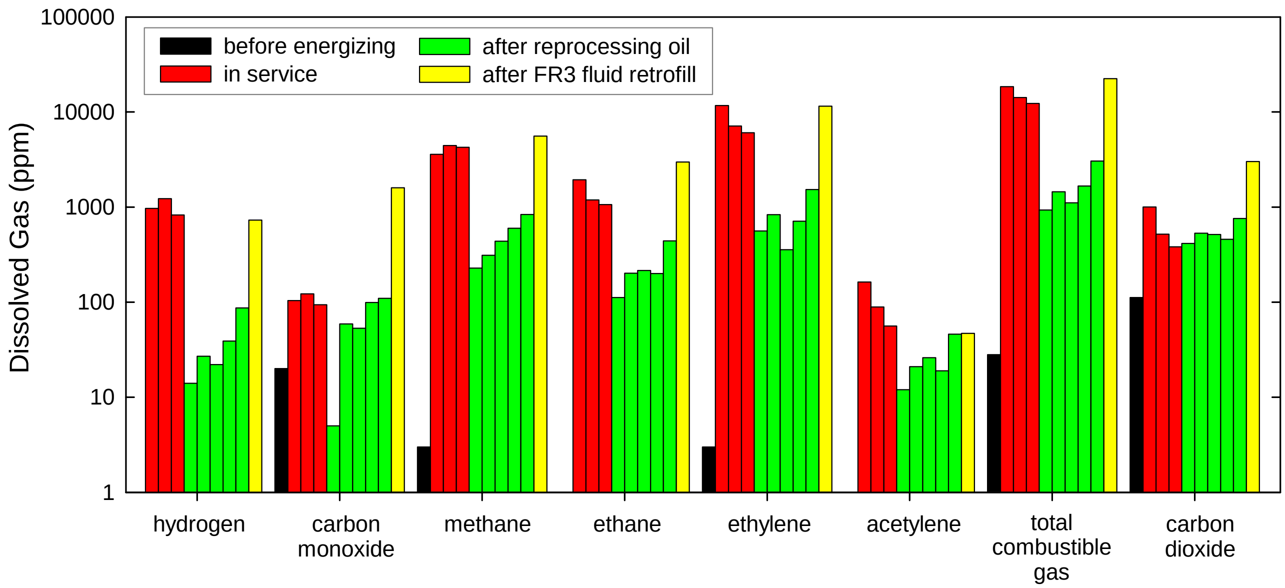


FIGURE A4. The mineral oil in the transformer was replaced with Envirotemp FR3 fluid (yellow bars). The initially gas-free fluid showed high combustible gas levels within 4 months of the retrofill. The amounts of gases generated by the fault in Envirotemp FR3 fluid are equivalent to those in mineral oil.

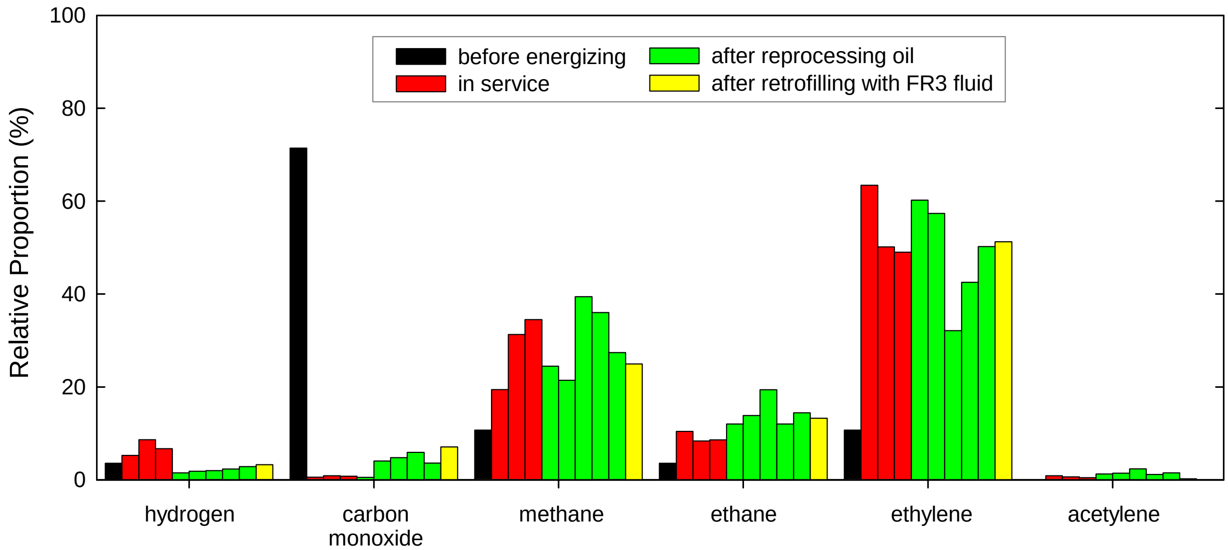
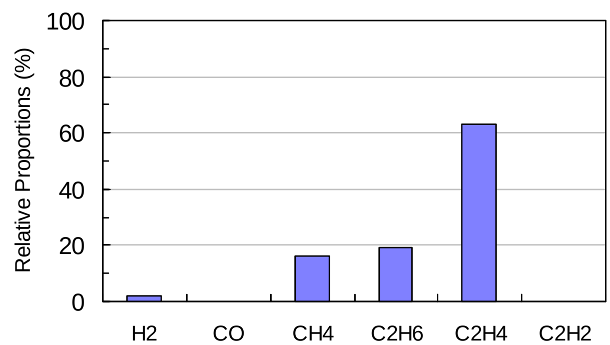


FIGURE A5. Proportions of combustible gases in Envirotemp FR3 fluid and mineral oil are similar and typical of a hot metal fault.

FIGURE A6. IEEE example of "Key Gases" thermal fault in oil proportions. Decomposition products include ethylene and methane, together with smaller quantities of hydrogen and ethane. Traces of acetylene may be form if the fault is severe or involves electrical contacts. Principle gas: ethylene.



Fault Type		Designation
Discharge	partial	PD
	low energy	D1
	high energy	D2
Thermal	T < 300°C (hot spot in paper)	T1
	300°C < T < 700°C (hot spot in paper)	T2
	T > 700°C (hot spot in oil)	T3
Mixed		DT

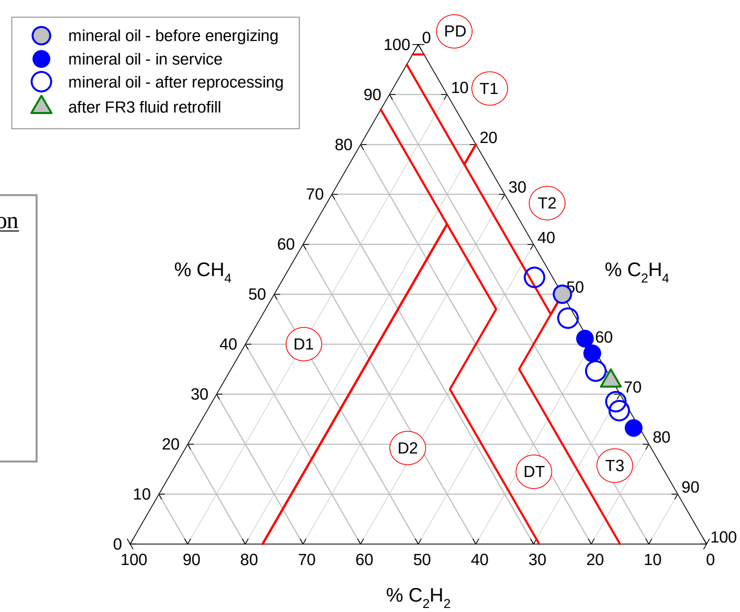


FIGURE A7. A Duval plot assigns the same fault type for mineral oil and Envirotemp FR3 fluid.

TABLE A1. IEEE methods applied to a factory-faulted mineral oil transformer retrofilled with Envirotemp FR3 fluid. Fault indications are similar for mineral oil and Envirotemp FR3 fluid.

	Mineral oil									FR3 Fluid
	Before Installation	In Service			After Reprocessing Oil					After Retrofill
Method	Jan '02	Oct '02	Nov '02	Dec '02	Feb `03	May `03	Jul `03	Oct `03	Jan `04	May `04
Condition										
H_2	1	3	3	3	1	1	1	1	1	3
CH_4	1	4	4	4	2	2	3	3	3	4
C_2H_6	1	4	4	4	3	4	4	4	4	4
C_2H_4	1	4	4	4	4	4	4	4	4	4
C_2H_2	1	4	4	3	1	1	1	1	2	2
CO	1	1	1	1	1	1	1	1	1	4
CO_2	1	1	1	1	1	1	1	1	1	2
TDCG[a]	1	4	4	4	2	2	2	2	3	4
Ratio										
Doerenburg	n/a[b]	thermal fault ⟶								⟶
Rogers	n/a	Case 5[c]	Case 5	Case 5	Case 5	Case 5	Case 4[d]	Case 5	Case 5	Case 5
CO_2/CO	n/a ⟶									⟶
Key Gases	n/a	thermal fault - oil ⟶								⟶

[a] TDCG: total dissolved combustible gas
[b] n/a: not applicable
[c] Case 5: thermal fault > 700 °C
[d] Case 4: thermal fault < 700 °C

TABLE A2. IEC methods applied to a factory-faulted transformer yield the same results for the transformer with mineral oil and after retrofilling the transformer with Envirotemp FR3 fluid.

	Mineral oil									FR3 Fluid
	Before Installation	In Service			After Reprocessing Oil					After Retrofill
Method	Jan '02	Oct '02	Nov '02	Dec '02	Feb `03	May `03	Jul `03	Oct `03	Jan `04	May `04
Duval	T2[a]/T3[b]	T3	T3	T3	T3	T3	T2	T3	T3	T3
Basic	T2	T3	T3	T3	T3	T3	T2	T2	T2	T2
Simplified	T[c] ⟶									⟶

[a] T2: thermal fault, 300°C < T < 700°C
[b] T3: thermal fault, T > 700°C
[c] T: thermal fault

Example B

Lightning Strike

A 25 kVA pole mount transformer filled with Envirotemp FR3 failed after a nearby lightning strike. It was returned to the factory for analysis. The dissolved gases found in the Envirotemp FR3 fluid were consistent with those expected in a similarly faulted mineral oil transformer. The IEEE Key Gases method was the only IEEE gas guide method to indicate the fault. The IEC Duval and Simplified ratio methods both indicate a discharge fault.

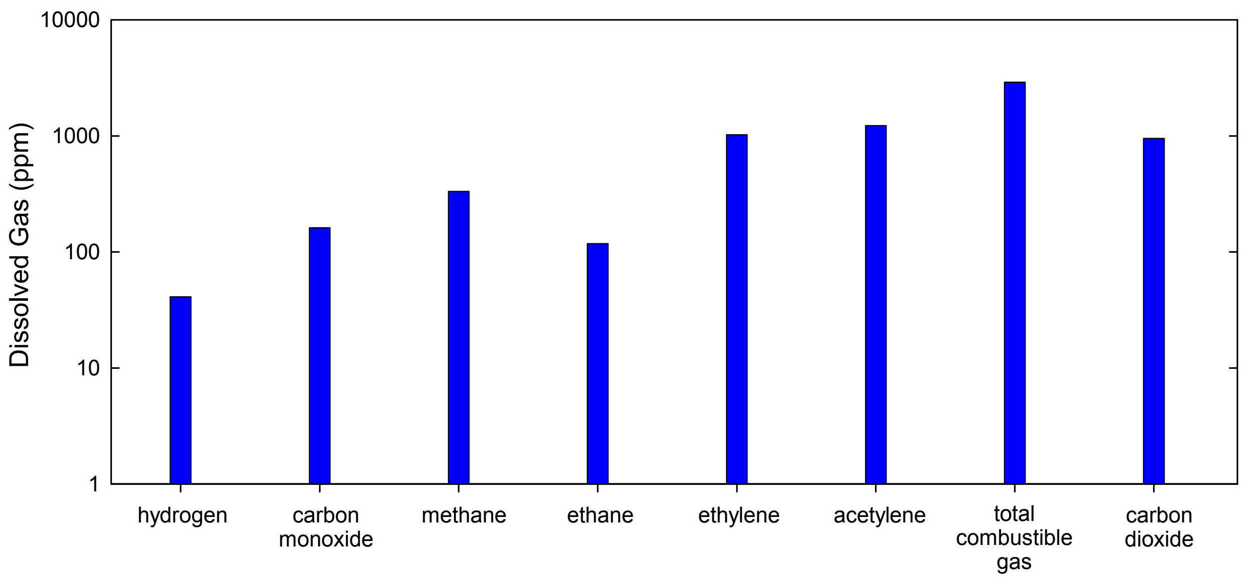


Figure B1. High levels of dissolved hydrocarbon gases, especially ethylene and acetylene.

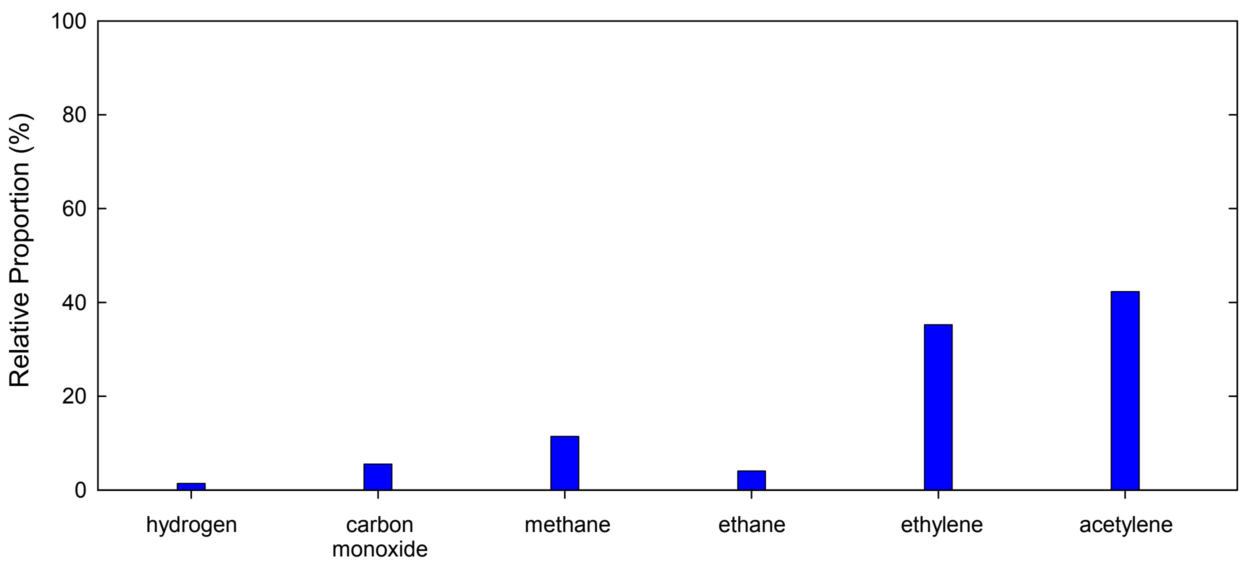


Figure B2. IEEE Key Gases proportions indicate a combination of faults: arcing and a thermal fault in oil.

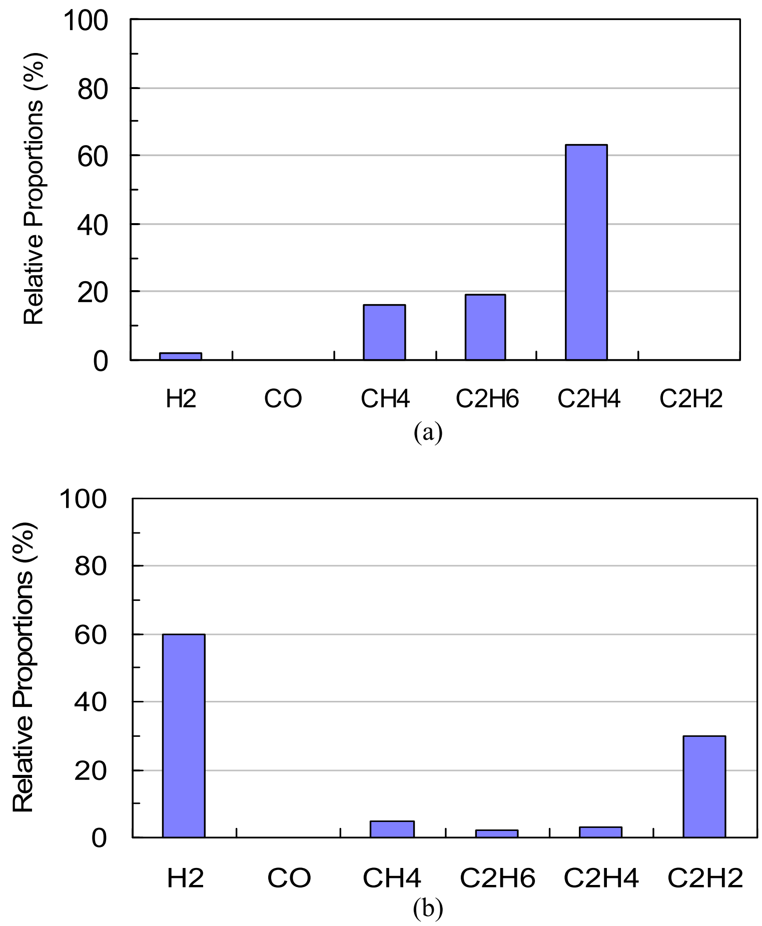


Figure B3. Typical IEEE "Key Gases" signatures for a thermal fault in oil (a) and arcing (b).

Fault Type		Designation
Discharge	partial	PD
	low energy	D1
	high energy	D2
Thermal	T < 300ºC (hot spot in paper)	T1
	300ºC < T < 700ºC (hot spot in paper)	T2
	T > 700ºC (hot spot in oil)	T3
Mixed		DT

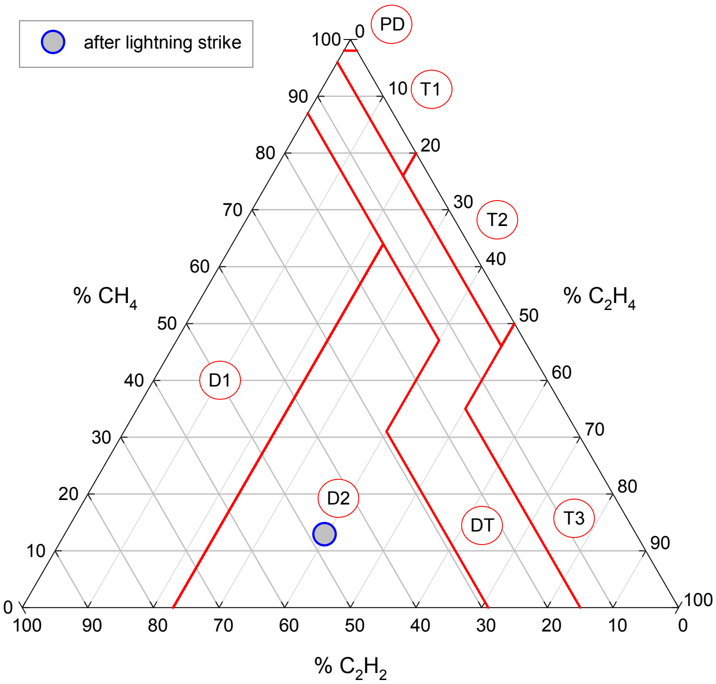


Figure B4. IEC Duval plot indicates high-energy discharge, consistent with a lightning strike.

Table B1. Results of IEEE and IEC methods

IEEE Method		IEC Method	
Ratio		Duval	D2[a]
Doerenburg	fni[b]	Basic	n/a[c]
Rogers	n/a	Simplified	D[d]
CO_2/CO	n/a		
Key Gases	thermal fault - oil, arcing		
Condition			
H_2	1		
CH_4	2		
C_2H_6	3		
C_2H_4	4		
C_2H_2	4		
CO	1		
CO_2	1		
TDCG[e]	3		

[a] D2: high energy discharge
[b] fni: ratio is applicable, fault not identifiable
[c] n/a: not applicable
[d] D: discharge
[e] TDCG: total dissolved combustible gas

Example C

Retrofilled transformer with coked contacts (no-load tap changer switch)

A 28-year-old mineral oil transformer was retrofilled in May 1998 with Envirotemp FR3 fluid. No dissolved gas history was available for the transformer. During the retrofill process, it was noted that the tap changer contacts showed significant coking. After a year in service, a large increase in gassing rates and high levels of acetylene were found (Figure C1). After verifying the dissolved gas levels, an outage was scheduled to examine the transformer. The tap changer contacts were heavily coked. The switch was replaced and new Envirotemp FR3 fluid added. After this maintenance, the gases returned to normal stable levels (Figure C2).

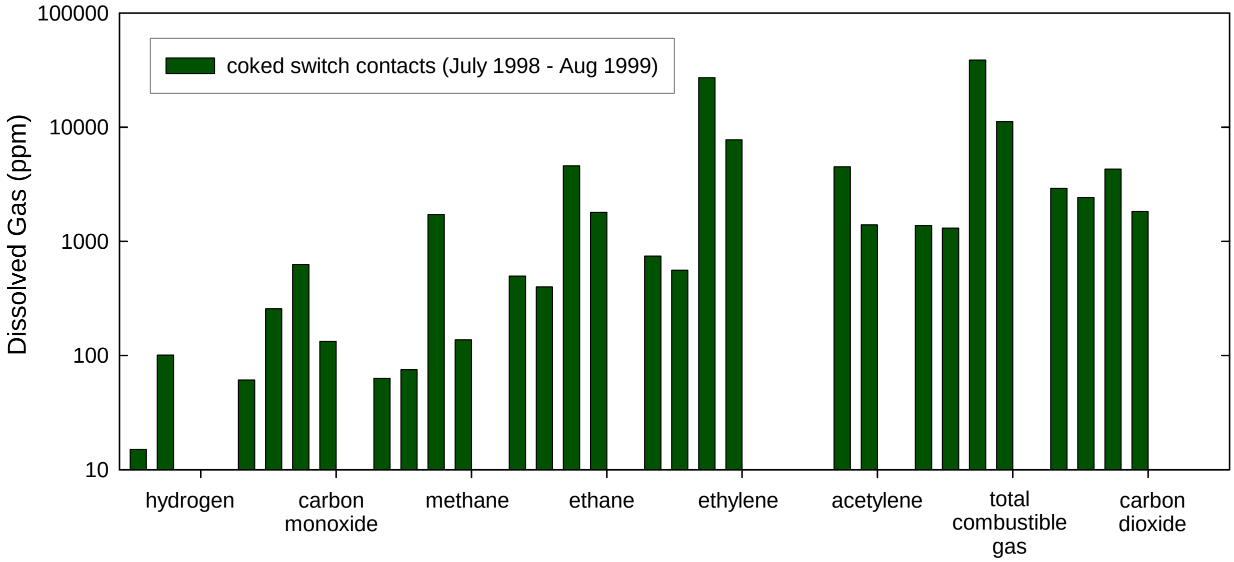


Figure C1. Dissolved combustible gas levels of a 28-year old mineral oil transformer after retrofilling with Envirotemp FR3 fluid. The high amount of acetylene found during routine sampling in July 1999 was verified by taking a second sample. An outage was scheduled, during which heavily coked tap changer contacts were found. The tap changer switch was replaced.

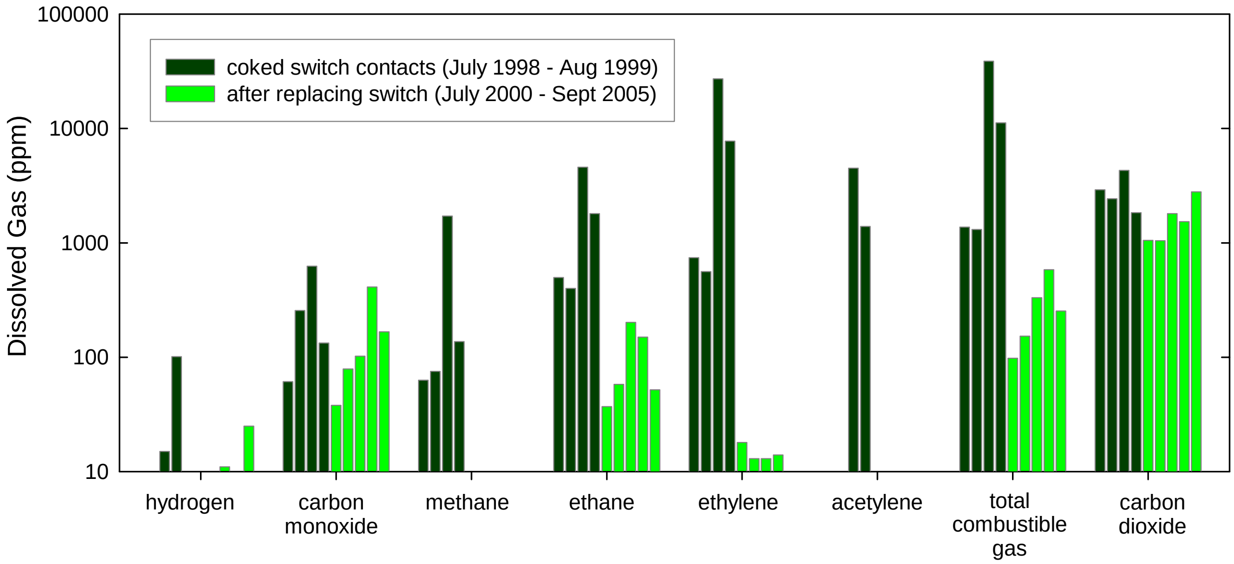


Figure C2. After replacing the tap changer switch and refilling with new Envirotemp FR3 fluid, the subsequent dissolved gas levels returned to normal (dark green bars).

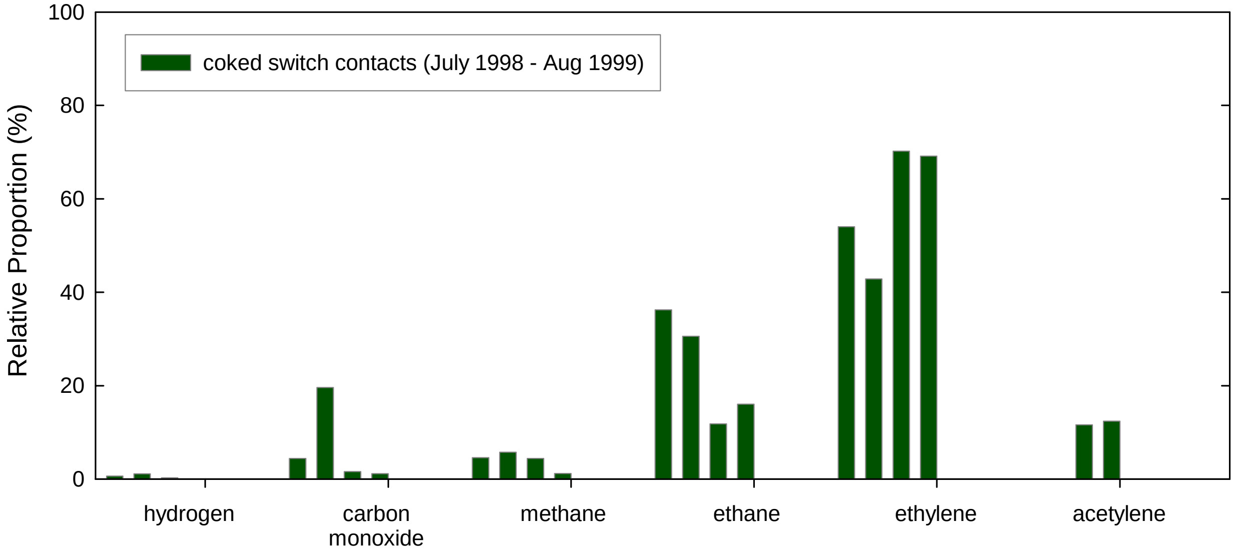


Figure C3. Proportions of combustible gases in Envirotemp FR3 fluid before switch maintenance are typical of those seen in a hot metal fault in mineral oil.

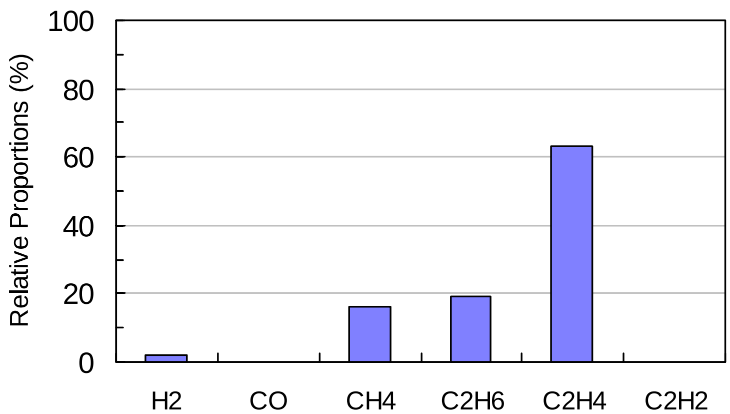


Figure C4. IEEE "Key Gases" example of the gas proportions seen in a typical thermal fault in mineral oil. Decomposition products include ethylene and methane, together with smaller quantities of hydrogen and ethane. Traces of acetylene may be formed if the fault is severe or involves electrical contacts. Principle gas: ethylene.

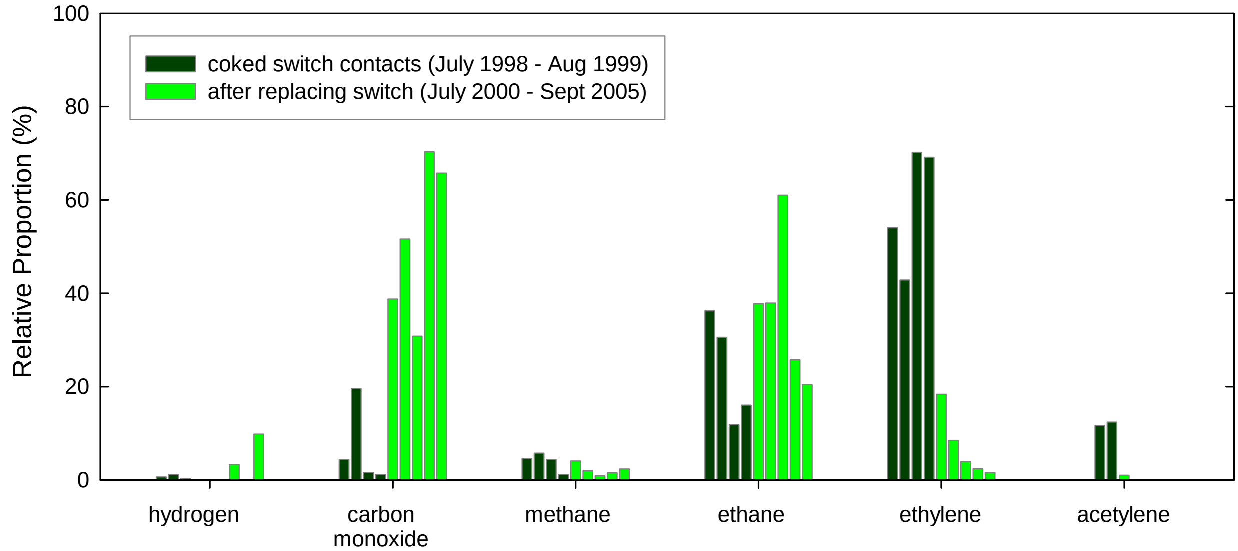


Figure C5. Proportions of combustible gases in Envirotemp FR3 fluid return to normal after transformer maintenance. Note that the ethane proportion would be atypical for a normally operating mineral oil transformer, but is commonly seen in normally operating Envirotemp FR3 fluid transformers.

Fault Type		Designation
Discharge	partial	PD
	low energy	D1
	high energy	D2
Thermal	T < 300°C (hot spot in paper)	T1
	300°C < T < 700°C (hot spot in paper)	T2
	T > 700°C (hot spot in oil)	T3
Mixed		DT

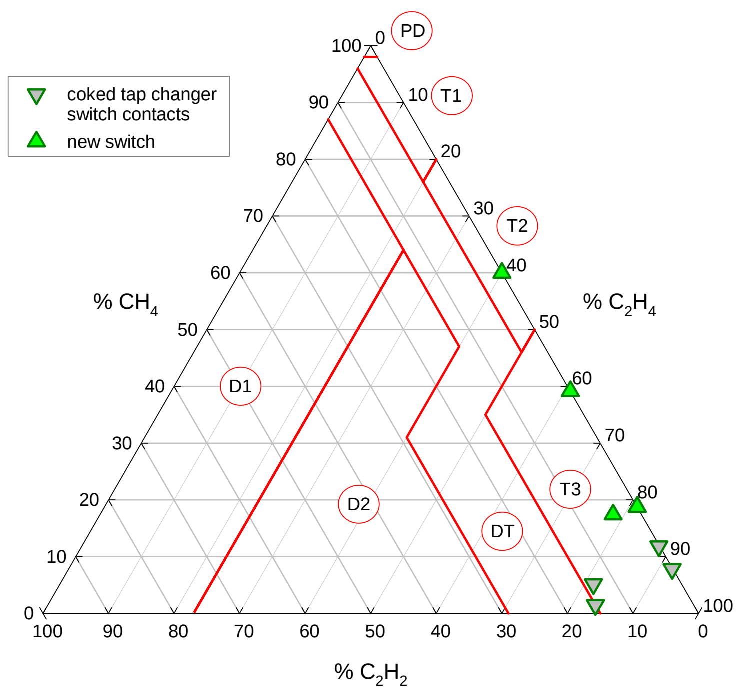


Figure C6. Duval plot indicates fault T3, or hot metal fault, in Envirotemp FR3 fluid. This indication is consistent with coked switch contacts.

Table C1. Results of IEEE methods: the “Key Gases” and “Condition” methods indicate the correct fault type in Envirotemp FR3 fluid in this example.

Method	July '98	Feb '99	July '99	Aug '99	July `00	July `01	July `02	July `03	Sept ‘05
Condition									
H_2	1	1	2	1	1	1	1	1	1
CH_4	1	1	4	2	1	1	1	1	1
C_2H_6	4	4	4	4	1	1	4	3	1
C_2H_4	4	4	4	4	1	1	1	1	1
C_2H_2	1	1	4	4	1	1	1	1	1
CO	1	1	3	1	1	1	1	2	1
CO_2	2	1	3	1	1	1	1	1	2
TDCG[a]	2	2	4	4	1	1	1	1	1
Ratio									
Doerenburg	n/a[b]	n/a	fni[c]	no indication	n/a ⟶				⟶
Rogers	Case 4[d]	Case 4	n/a	n/a	n/a	n/a	Case 0[e]	n/a	Case 0
CO_2/CO	n/a ⟶								⟶
Key Gases	thermal fault - oil ⟶			⟶	no fault ⟶				⟶

[a] TDCG: total dissolved combustible gas
[b] n/a: not applicable —
[c] fni: ratio is applicable, fault not identifiable
[d] Case 4: thermal fault < 700 °C
[e] Case 0: no fault

Table C2. When the fault exists, the IEC methods indicate the correct fault type in this example. Note that the presence of a fault must be known. The ratios indicate a fault type when no fault exists.

Method	July '98	Feb '99	July '99	Aug '99	July `00	July `01	July `02	July `03	Sept ‘05
Duval	T3[a]	T3	T3	DT[b]	T3	T3	T3	T3	T2
Basic	T2[c]	T2	T3	n/a[d]	T1[e]	T1	T1	T1	T1
Simplified	T[f] ⟶								⟶

[a] T3: thermal fault, T > 700°C
[b] DT: mixed faults
[c] T2: thermal fault, 300°C < T < 700°C
[d] n/a: not applicable
[e] T1: thermal fault, T < 300°C
[f] T: thermal fault

Example D

Retrofilled Pad Mount Transformer

A 25-year-old 225 KVA 3-phase pad mount mineral oil transformer was retrofilled in May 1998 with Envirotemp FR3 fluid. No dissolved gas history was available for the transformer. The transformer has been routinely monitored since the retrofill. The amounts of dissolved combustible gases have remained unchanged, indicating stable operation. The proportion of ethane compared to methane and ethylene is higher than is typically seen in mineral oil, but common in normally operating Envirotemp FR3 fluid transformers.

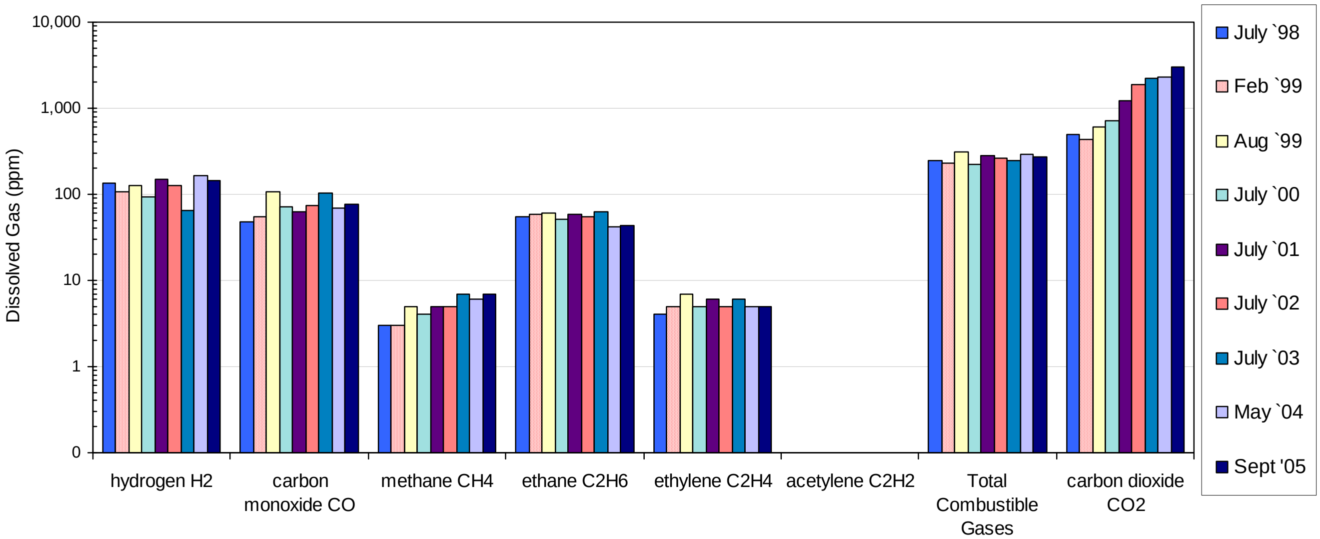


Figure D1. Amounts of dissolved combustible gases are stable over time. Hydrogen is a bit higher than is typical for a normally operating mineral oil transformer, but is occasionally seen in Envirotemp FR3 transformers.

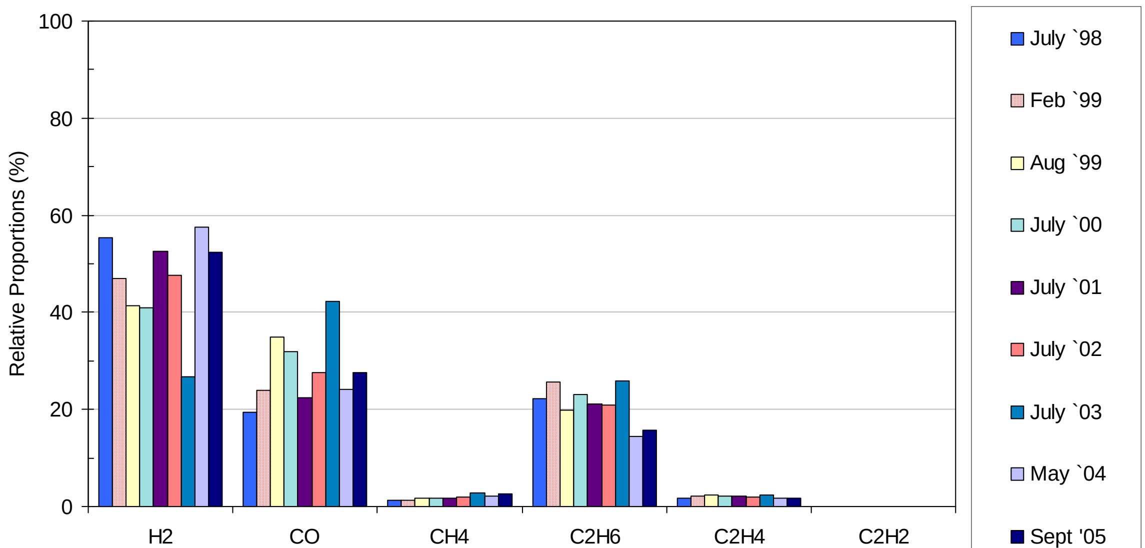


Figure D2. “Key Gases” proportions show the higher proportion of ethane commonly seen in Envirotemp FR3 transformers.

Table D1. IEEE methods applied to a normally operating mineral oil transformer retrofilled with Envirotemp FR3 fluid.

Method	July 1998	Feb 1999	Aug 1999	July 2000	July 2001	July 2002	July 2003	May 2004	Sept 2005
Condition									
H_2	2	2	2	1	2	2	1	2	2
CH_4	1	→	→	→	→	→	→	→	→
C_2H_6	1	→	→	→	→	→	→	→	→
C_2H_4	1	→	→	→	→	→	→	→	→
C_2H_2	1	→	→	→	→	→	→	→	→
CO	1	→	→	→	→	→	→	→	→
CO_2	1	→	→	→	→	→	→	→	2
TDCG[a]	1	→	→	→	→	→	→	→	→
Ratio									
Doerenburg	n/a[b]	→	→	→	→	→	→	→	→
Rogers	Case 1[c]	Case 1	Case 1	Case 1	Case 1	Case 1	Case 0[d]	Case 1	Case 1
CO_2/CO	n/a	→	→	→	→	→	→	→	→
Key Gases	n/a	→	→	→	→	→	→	→	→

[a] TDCG: total dissolved combustible gas
[b] n/a: not applicable
[c] Case 1: partial discharge
[d] Case 0: no fault

Table D2. IEC methods applied to a normally operating mineral oil transformer retrofilled with Envirotemp FR3 fluid. Note that the ratios indicate a fault type regardless of transformer condition.

Method	July 1998	Feb 1999	Aug 1999	July 2000	July 2001	July 2002	July 2003	May 2004	Sept 2005
Duval	T3[a]	T3	T3	T3	T3	T3/T2[b]	T2	T2	T2
Basic	T1[c]/PD[d]	T1/PD	T1/PD	T1/PD	T1/PD	T1/PD	T1	T1/PD	T1/PD
Simplified	T[e]/PD	→	→	→	→	→	→	→	→

[a] T3: thermal fault, T > 700°C
[b] T2: thermal fault, 300°C < T < 700°C
[c] T1: thermal fault, T < 300°C
[d] PD: partial discharge
[e] T: thermal fault

Example E

New Pad Mount Transformer

A new 225 kVA 3-phase pad mount transformer filled with Envirotemp FR3 was installed in June 1996 and monitored periodically since. The combustible gas generation rates are nil, indicating stable operation. Note the increase in carbon oxide gases due to normal transformer aging.

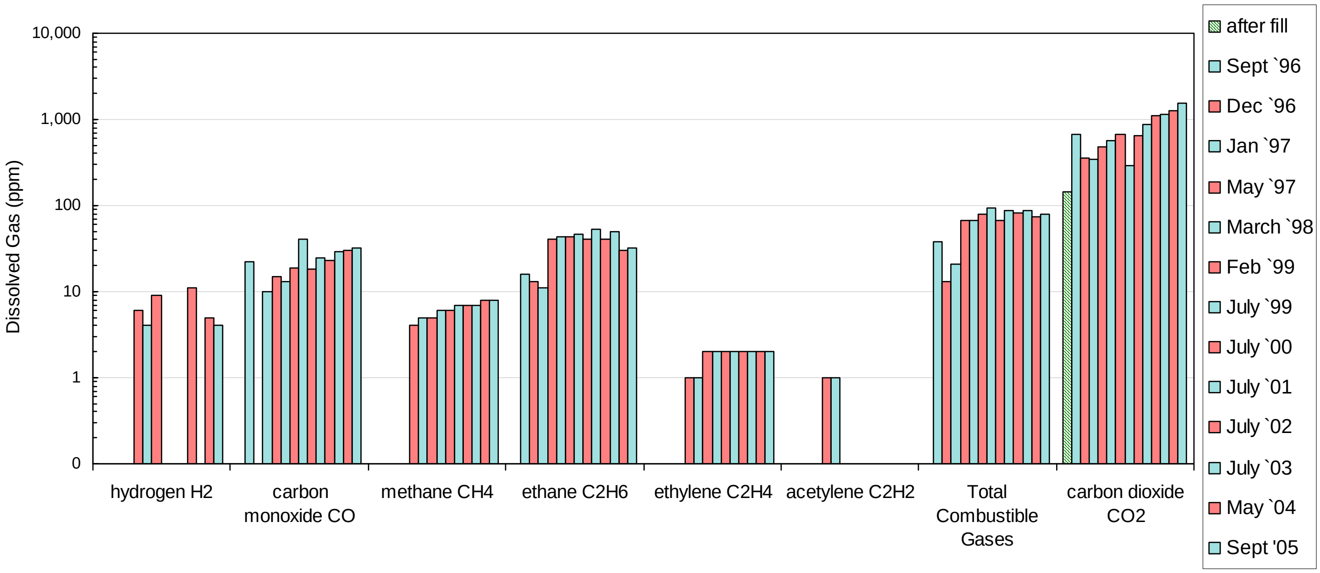


Figure E1. The levels of combustible gases remains essentially unchanged, indicating stable operation.

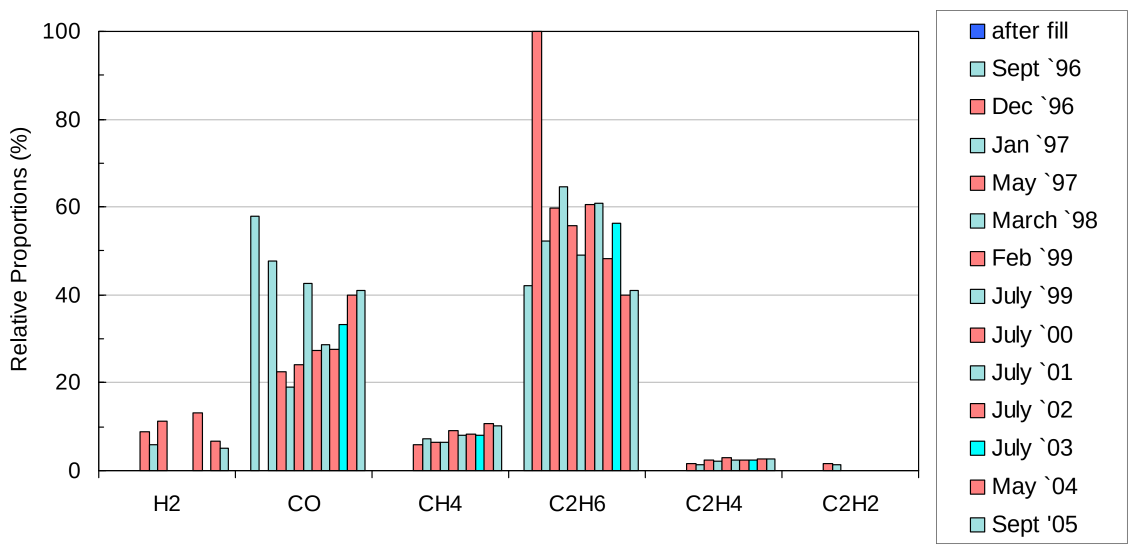


Figure E2. “Key Gases” proportions do not match a fault signature. Note that the ethane proportion would be atypical for a normally operating mineral oil transformer, but is commonly seen in normally operating Envirotemp FR3 fluid transformers.

Table E1. IEEE methods applied to a normally operating Envirotemp FR3 fluid transformer.

Method	after fill	Sept 1996	Dec 1996	Jan 1997	May 1997	Mar 1998	Feb 1999	July 1999	July 2000	July 2001	July 2002	July 2003	May 2004	Sept 2005
Condition														
H_2	1	→												
CH_4	1	→												
C_2H_6	1	→												
C_2H_4	1	→												
C_2H_2	1	→												
CO	1	→												
CO_2	1	→												
TDCG[a]	1	→												
Ratio														
Doerenburg	n/a[b]	→												
Rogers	n/a	n/a	n/a	n/a	n/a	n/a	Case 0[c]	n/a	n/a	Case 0	n/a	n/a	n/a	n/a
CO_2/CO	n/a	→												
Key Gases	n/a	→												

[a] TDCG: total dissolved combustible gas
[b] n/a: not applicable
[c] Case 0: no fault

Table E2. IEC methods applied to a normally operating Envirotemp FR3 fluid transformer.

Method	after fill	Sept 1996	Dec 1996	Jan 1997	May 1997	Mar 1998	Feb 1999	July 1999	July 2000	July 2001	July 2002	July 2003	May 2004	Sept 2005
Duval	n/a[a]	n/a	n/a	n/a	D1[b]	D1	T2[c]	T2	T2	T2	T2	T2	T1[d]	T1
Basic	n/a	T1	→											
Simplified	n/a	n/a	n/a	n/a	D[e]	D	T[f]	→						

[a] n/a: not applicable
[b] D1: low energy discharge
[c] T2: thermal fault, 300°C < T < 700°C
[d] T1: thermal fault, T < 300°C
[e] D: discharge
[f] T: thermal fault

Example F

New Pad Mount Transformer #2

A new 225 kVA 3-phase pad mount transformer filled with Envirotemp FR3 was installed in June 1996 and monitored periodically since. The combustible gas generation rates are nil, indicating stable operation. This transformer exhibits both the higher proportion of ethane commonly seen and the somewhat elevated hydrogen content occasionally seen in normally operating Envirotemp FR3 fluid transformers. Note the increase in carbon oxide gases due to normal transformer aging.

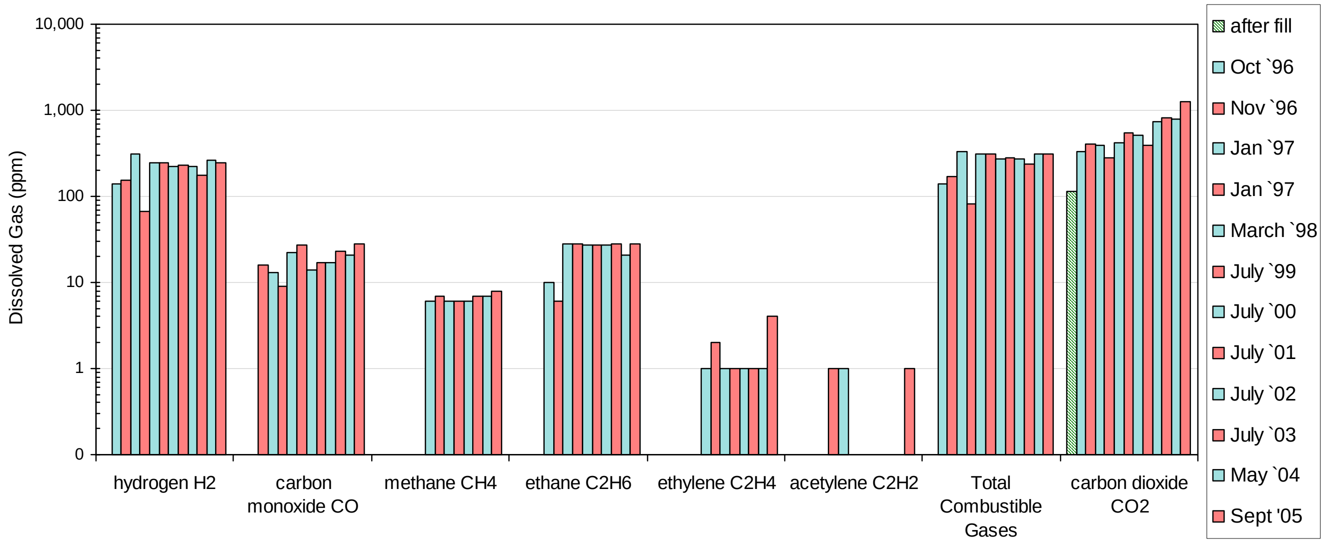


Figure F1. The amounts of dissolved combustible gases remain essentially unchanged. The amount of hydrogen is higher than might be expected in a normally operating mineral oil transformer, but is sometimes seen in Envirotemp FR3 fluid.

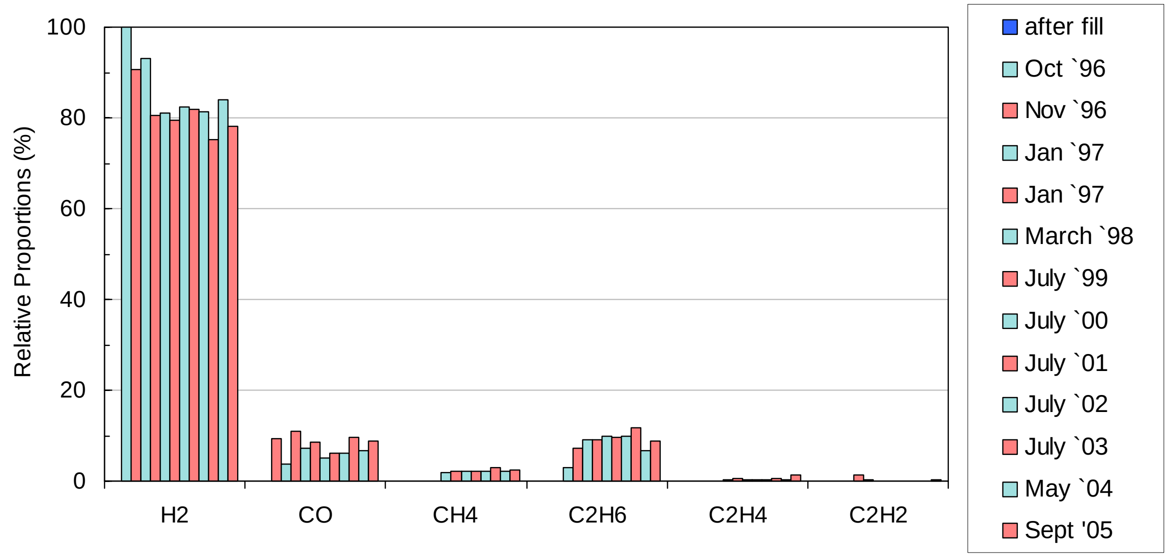


Figure F2. “Key Gases” proportions match the signature of a partial discharge fault. The low gassing rate indicates no active fault is present. Note the high proportion of ethane to methane and ethylene, commonly seen in normally operating Envirotemp FR3 fluid transformers.

Table F1. IEEE methods applied to a normally operating transformer with Envirotemp FR3 fluid. The slightly elevated hydrogen content is reflected in the Condition and Rogers results.

Method	June 1996	Oct 1996	Nov 1996	Jan 1997	Mar 1998	July 1999	July 2000	July 2001	July 2002	July 2003	May 2004	Sept 2005
Condition												
H_2	1	2	2	2	1	2	→	→	→	→	→	→
CH_4	1	→	→	→	→	→	→	→	→	→	→	→
C_2H_6	1	→	→	→	→	→	→	→	→	→	→	→
C_2H_4	1	→	→	→	→	→	→	→	→	→	→	→
C_2H_2	1	→	→	→	→	→	→	→	→	→	→	→
CO	1	→	→	→	→	→	→	→	→	→	→	→
CO_2	1	→	→	→	→	→	→	→	→	→	→	→
TDCG[a]	1	→	→	→	→	→	→	→	→	→	→	→
Ratio												
Doerenburg	n/a[b]	→	→	→	→	→	→	→	→	→	→	→
Rogers	n/a	n/a	n/a	n/a	n/a	Case 1[c]	Case 1	Case 1	Case 1	Case 1	Case 1	n/a
CO_2/CO	n/a	→	→	→	→	→	→	→	→	→	→	→
Key Gases	corona	→	→	→	→	→	→	→	→	→	→	→

[a] TDCG: total dissolved combustible gas
[b] n/a: not applicable
[c] Case 1: partial discharge

Table F2. IEC methods applied to a normally operating transformer with Envirotemp FR3 fluid.

Method	June 1996	Oct 1996	Nov 1996	Jan 1997	Mar 1998	July 1999	July 2000	July 2001	July 2002	July 2003	May 2004	Sept 2005
Duval	n/a[a]	n/a	n/a	n/a	D1[b]	DT	T2[c]	T1	T2	T2	T2	DT
Basic	n/a	n/a	n/a	PD/T1	→	→	→	→	→	→	→	→
Simplified	n/a	PD	PD	PD	PD/D[e]	PD/T	PD/T	PD/T	PD/T	PD/T	PD/T	PD/D

[a] n/a: not applicable
[b] D1: low energy discharge
[c] T2: thermal fault, 300°C < T < 700°C
[d] T1: thermal fault, T < 300°C
[e] D: discharge
[f] T: thermal fault

Example G

Regulator Operational Life Test

Two identical voltage regulators were subjected to operational life test. One regulator was filled with mineral oil, the other with Envirotemp FR3 fluid. Fluid samples were taken after 60,000, 120,000, and 173,000 operations. Each operation consisted of a full cycle through the regulator span. Both fluids generated the same types and amounts of gases. IEEE Key Gases and IEC Duval methods correctly indicated low energy discharge in both fluids.

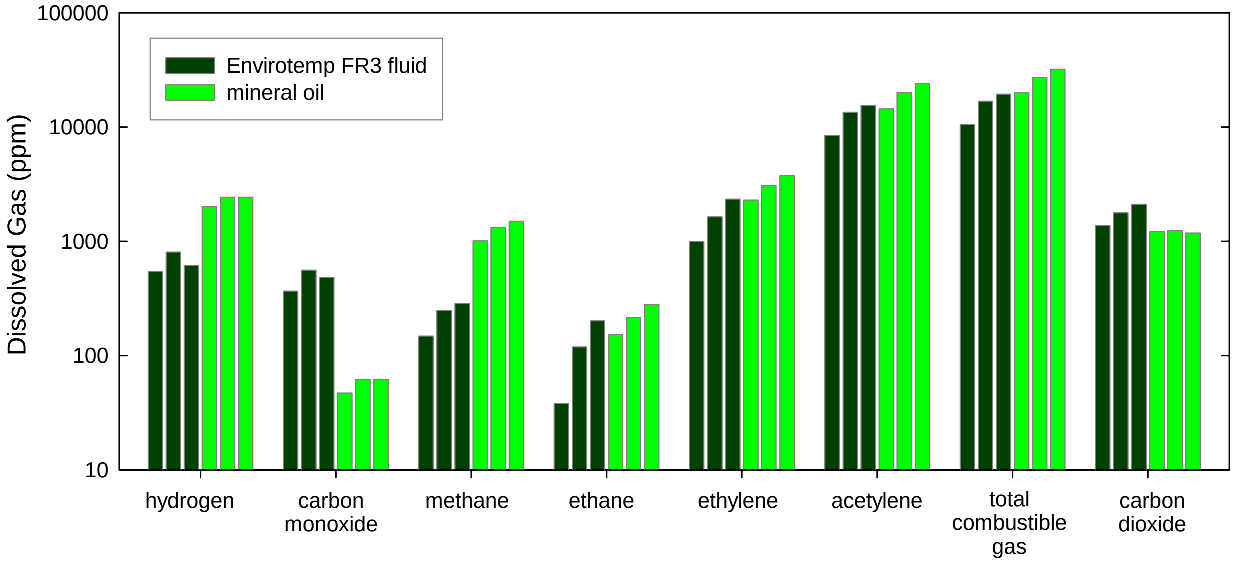


Figure G1. Dissolved gases generated in regulator life tests. Dark green bars are Envirotemp FR3 fluid; light green bars are mineral oil. Samples were taken after 60,000, 120,000, and 173,000 operations. One regulator operation consisted of a full cycle through the switches. Note the similarity between gases generated in mineral oil and Envirotemp FR3 fluid during regulator operation.

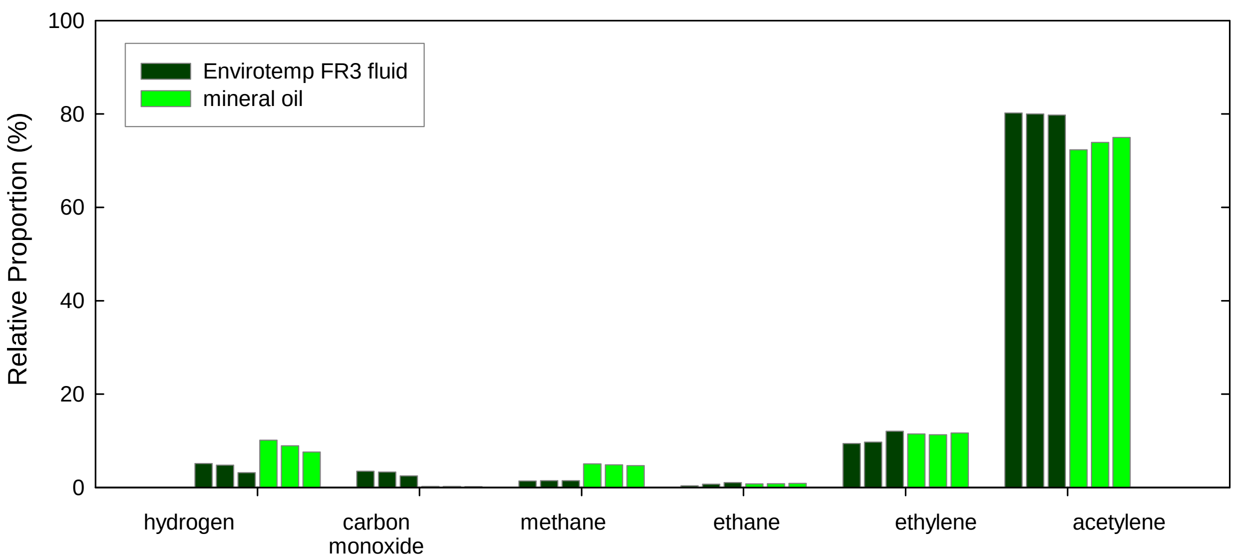


Figure G2. IEEE “Key Gases” proportions are the same for both fluids and match the IEEE signature for arcing.

Fault Type		Designation
Discharge	partial	PD
	low energy	D1
	high energy	D2
Thermal	T < 300°C (hot spot in paper)	T1
	300°C < T < 700°C (hot spot in paper)	T2
	T > 700°C (hot spot in oil)	T3
Mixed		DT

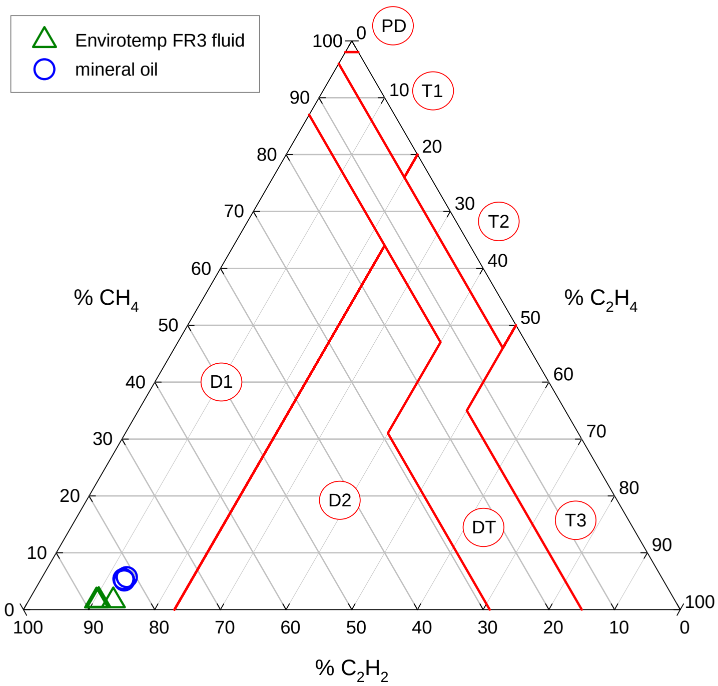


Figure G3. IEC Duval method correctly indicates low energy discharge for both fluids.

Table G1. IEEE methods applied to the gases generated during regulator life tests. The Doerenburg and Key Gases methods correctly indicated the presence of arcing in both fluids.

	Number of Complete Cycles					
	Envirotemp FR3 Fluid			Mineral Oil		
Method	60,000	120,000	173,000	60,000	120,000	173,000
Condition						
H_2	2	3	2	4	4	4
CH_4	2	2	2	4	4	4
C_2H_6	1	3	4	4	4	4
C_2H_4	4	4	4	4	4	4
C_2H_2	4	4	4	4	4	4
CO	2	2	2	1	1	1
CO_2	1	1	1	1	1	1
TDCG[a]	4	4	4	4	4	4
Ratio						
Doerenburg	DA[b]	DA	DA	DA	DA	DA
Rogers	n/a[c]	n/a	n/a	n/a	n/a	n/a
CO_2/CO	n/a	n/a	n/a	n/a	n/a	n/a
Key Gases	A[d]	A	A	A	A	A

[a] TDCG: total dissolved combustible gas
[b] DA: discharge arcing
[c] n/a: not applicable
[d] A: arcing

Table G2. IEC methods applied to the gases generated during regulator life tests. All methods indicated correctly for Envirotemp FR3 fluid. The Basic method did not consistently identify switch arcing in mineral oil.

	Number of Full Regulation Cycles					
	Envirotemp FR3 Fluid			Mineral Oil		
Method	60,000	120,000	173,000	60,000	120,000	173,000
Duval	D1[a]	D1	D1	D1	D1	D1
Basic	D1	D1	D1	D1	n/a[b]	n/a
Simplified	D[c]	D	D	D	D	D

[a] D1: low energy discharge
[b] n/a: not applicable
[c] D: discharge