Dissolved Gas Analysis (DGA)

Transformer Concepts & Applications Seminar

Goldsboro, NC

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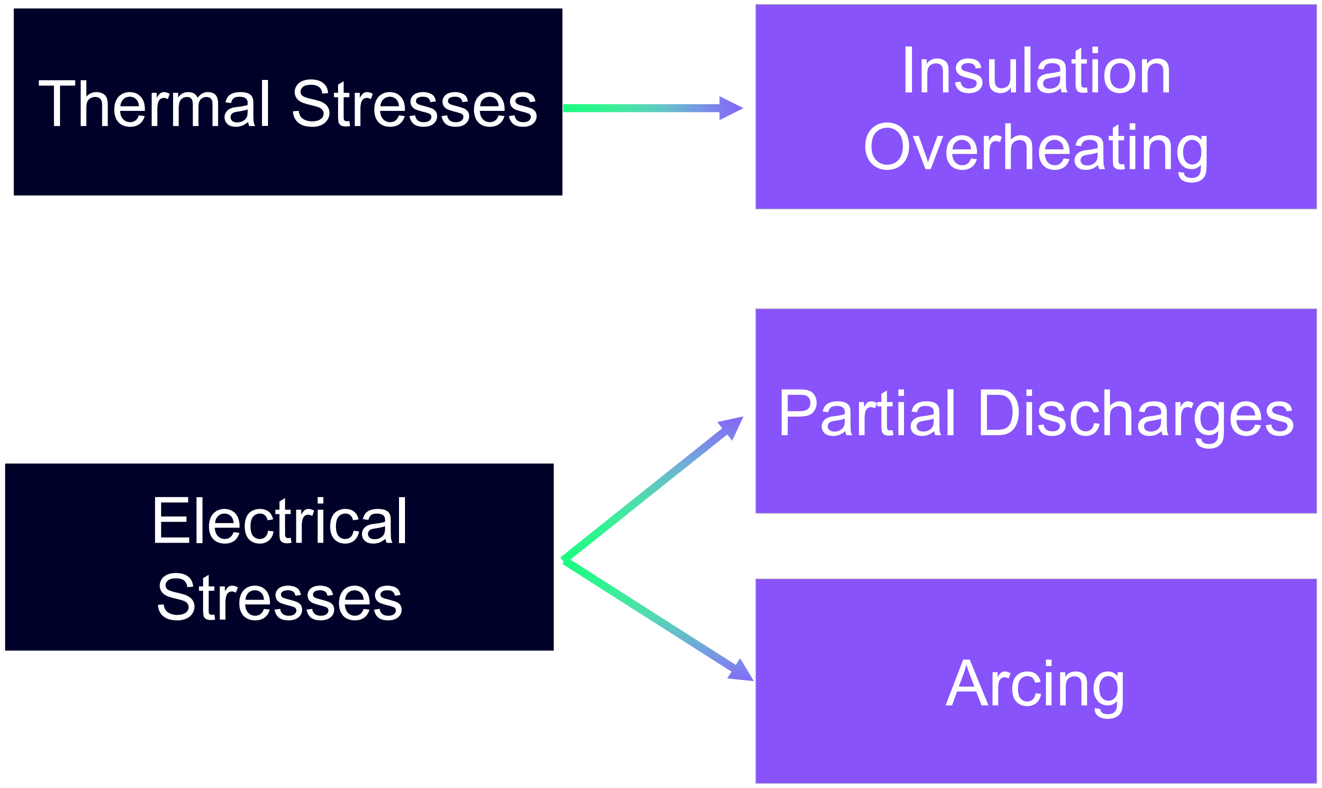
waukesha
a prolec ge company

Agenda

- Background
- Methods of Fault Gas Detection
- Why DGA?
- Gases of Interest
- DGA Technique
- Industry Standards
- Interpretation of DGA Results
- DGA Example
- Advantages
- Disadvantages
- Considerations
- Taking a DGA Sample
- Furans & Other Analyses
- Fault Examples

Background

Insulating materials (oil, paper, etc) inside a transformer breaks down from



Background

Fault categories:

- Localized overheating
- General overheating
- Partial Discharge/Corona
- Arcing

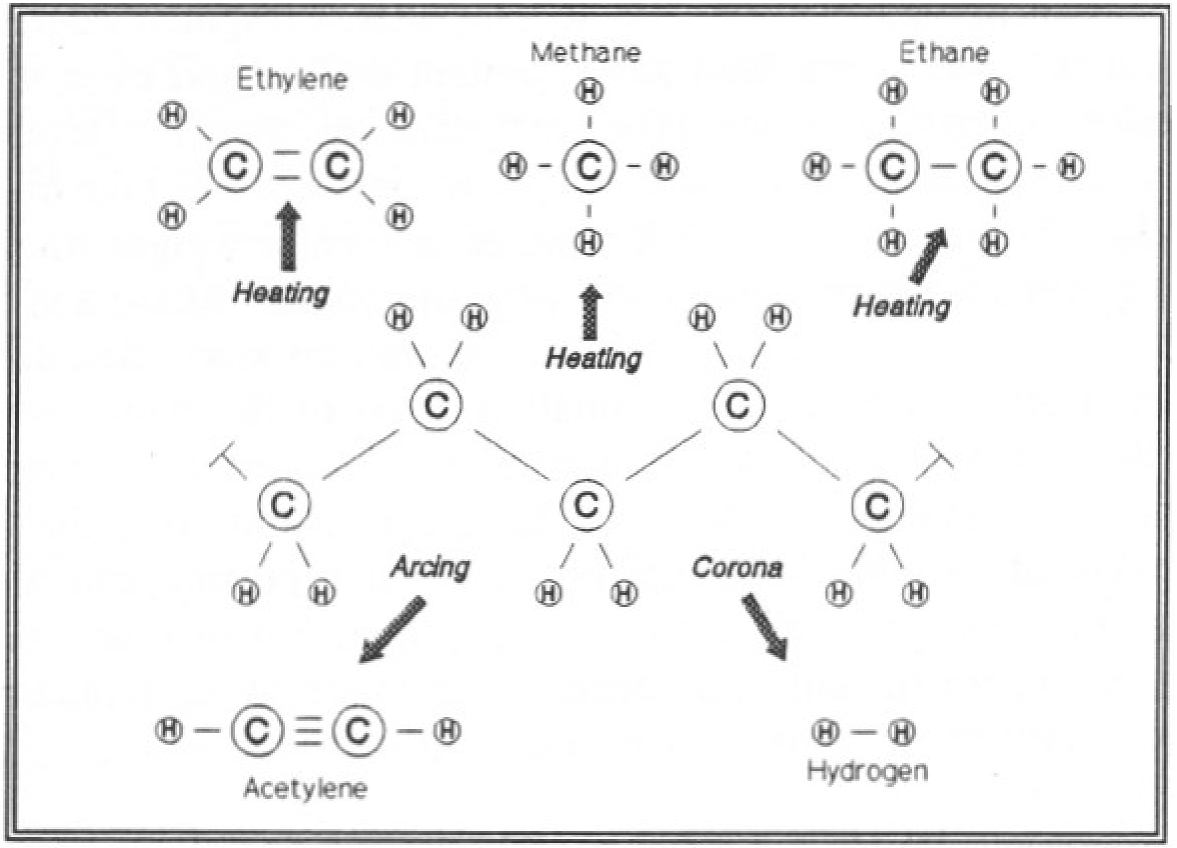
Fault Energy → Hydrocarbon Molecules → Hydrocarbon Gases

These gases can indicate:

- Fault condition
- Materials involved in the fault
- Severity of the fault condition

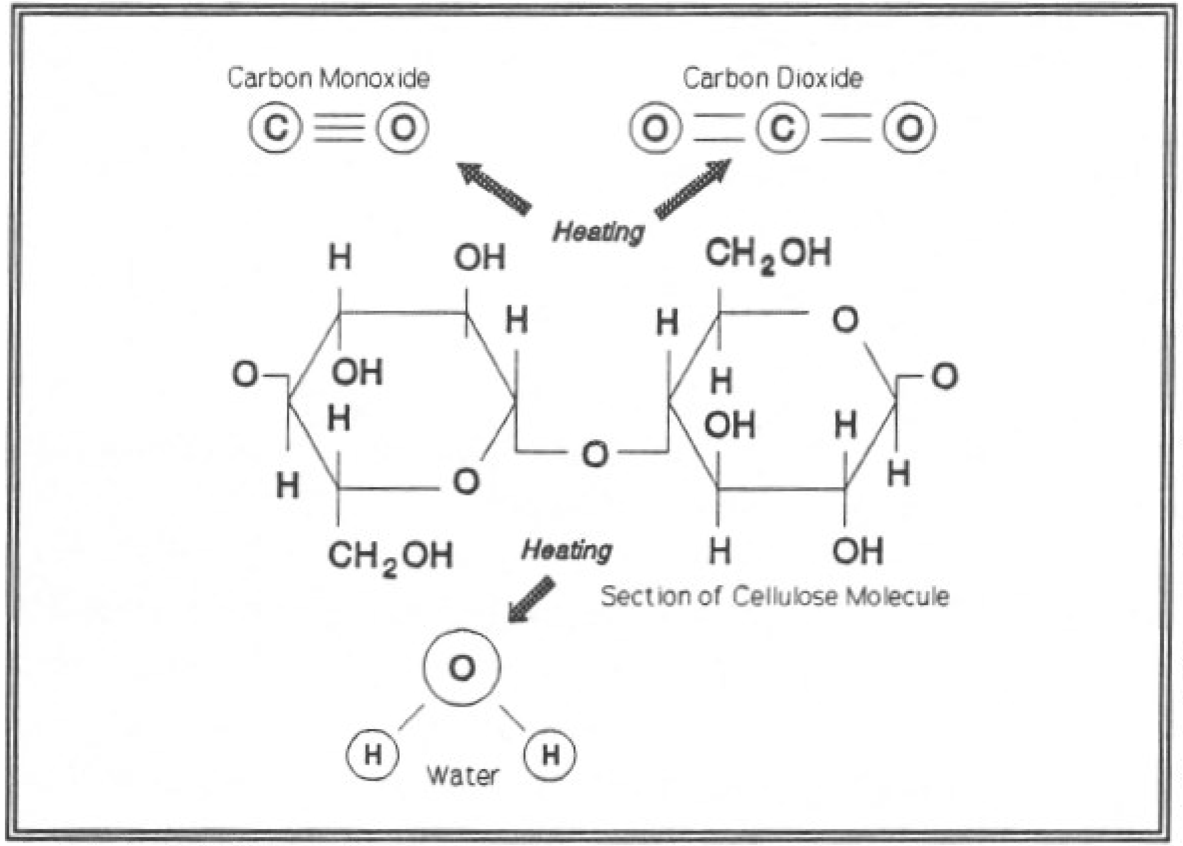
Background

Abnormal energy applied to mineral oil breaks some chemical bonds in the oil producing combustible gas.



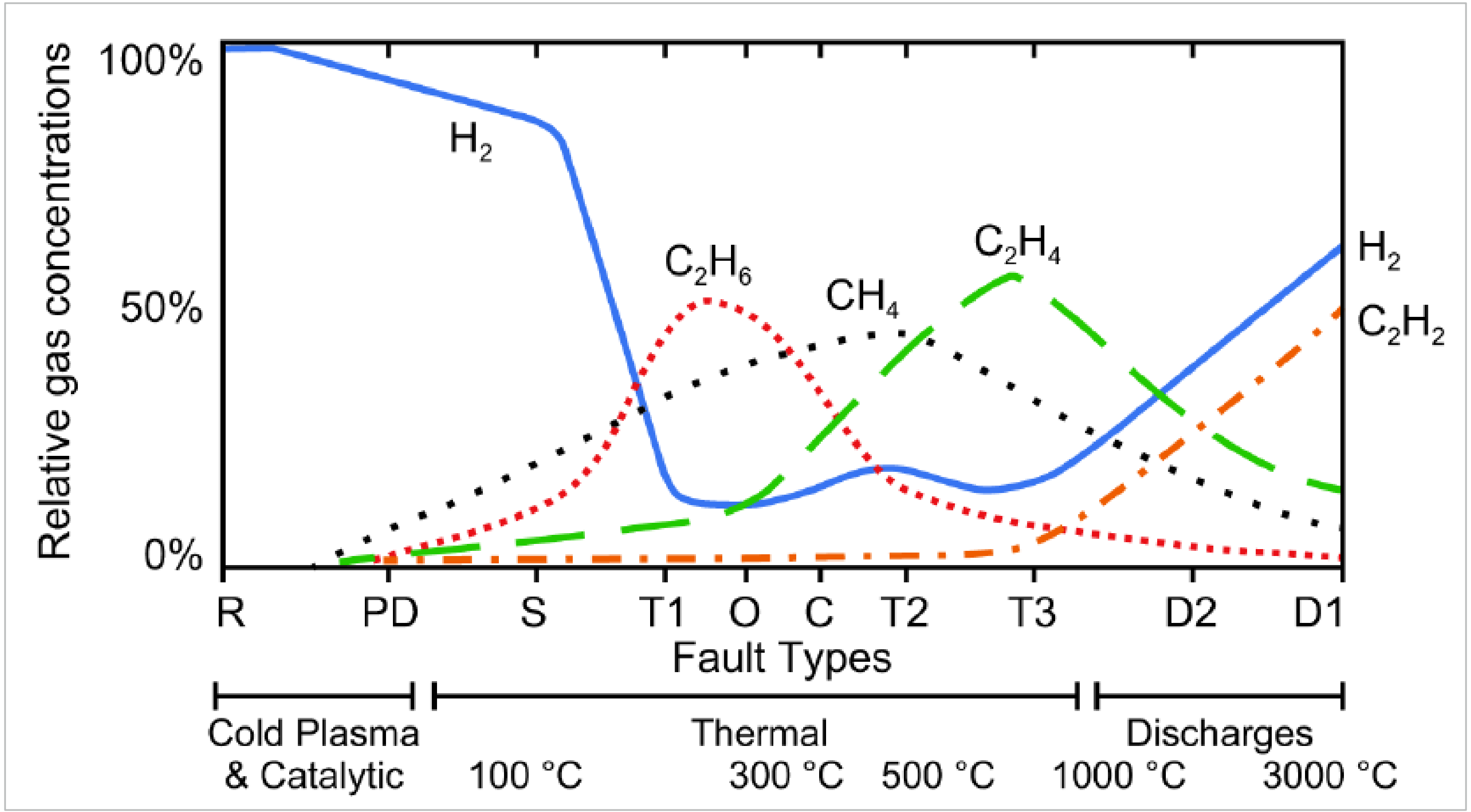
Background

Energy applied to insulation paper breaks some chemical bonds and produces Carbon Dioxide, Carbon Monoxide, Water and 'Furans'.

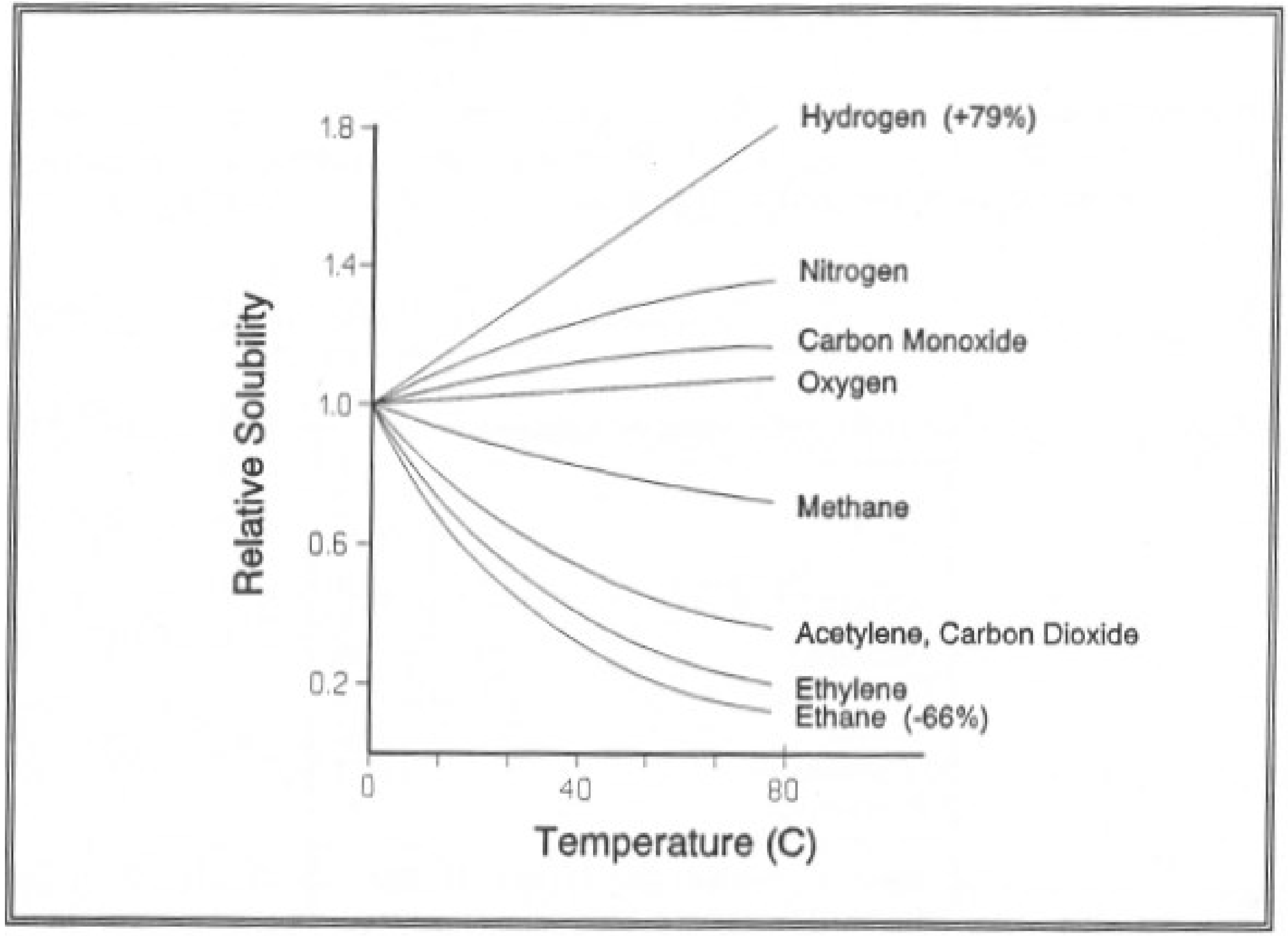


Background

Gas generation in oil verses temperature.



Saturation levels in oil vary with temperature based on curves below.



Solubility of Gases in Transformer Oil

(Percent by Volume)

H_2	Hydrogen	7.0
N_2	Nitrogen	8.6
CO_2	Carbon Monoxide	9.0
O_2	Oxygen	16
CH_4	Methane	30
CO_2	Carbon Dioxide	120
C_2H_6	Ethane	280
C_2H_4	Ethylene	280
C_2H_2	Acetylene	400

Static Equilibrium Pressure 1 Atmosphere at 25°C

Example: Oil will hold about 9 cu-ft of Nitrogen per 1000 gallons of oil.

Background

- Distribution of gases → Type of fault
- Rate of generation → Severity of fault

- By detecting and interpreting certain key gases and their ratios, transformer problems can be exposed.

- Data from fault gas analysis can provide
  a) Advance warning of incipient faults
  b) A means for conveniently scheduling repairs
  c) Monitor the rate of fault development
  d) Root cause investigations after failures have occurred

Methods of Fault Gas Detection

Physical gas formation	Interpretation of results
Known science	Years of empirical data

Two main methods of Sampling

a) Gas blanket over oil

b) From oil

Why DGA?

Disadvantages of gas blanket sampling

- Not all transformers have a gas blanket above oil
- Gas space concentrations must be converted to oil concentrations before interpretation
- Gases generated in the oil take time to partition into the gas space and achieve equilibrium
- TCG monitoring can provide an alarm and data and gas generation rate but not individual gases
- Interpretation ratios are different in the gas space vs. in oil

Gases of Interest

Enough useful information can be extracted from 9 gases:

Atmospheric Gasses

- Nitrogen (N_2)
- Oxygen (O_2
- Hydrogen (H_2)

Oxides of carbon

- Carbon Monoxide (CO)
- Carbon Dioxide (CO_2)

Hydrocarbons

- Methane (CH_4)
- Ethane (C_2H_6)
- Ethylene (C_2H_4)
- Acetylene (C_2H_2)

Gases of Interest *(cont.)*

- **Thermal Fault**
  - Insulation Overheating → Carbon Monoxide, Carbon Dioxide
  - Oil Overheating →
    - **Hydrogen**, Methane, Ethane < 150 C
    - **Hydrogen**, Ethylene, Trace Acetylene > 500C
- **Electrical Fault**
  - Partial Discharge →
    - **Hydrogen** and Methane
    - Small amounts of Ethane and Ethylene
  - Arcing →
    - **Hydrogen** and Acetylene
    - Small amounts of Ethane and Ethylene

DGA Technique

- Diagnostic technique useful for preventive maintenance
- Oil sample is extracted from the transformer
- Involves extracting the gases from the oil and injecting them into an equipment called gas chromatograph

Industry Standards

Standards associated with DGA:

Sampling → ASTM D3613

Testing → ASTM D3612

Analyzing → IEEE C57.104

Interpretation of DGA Results

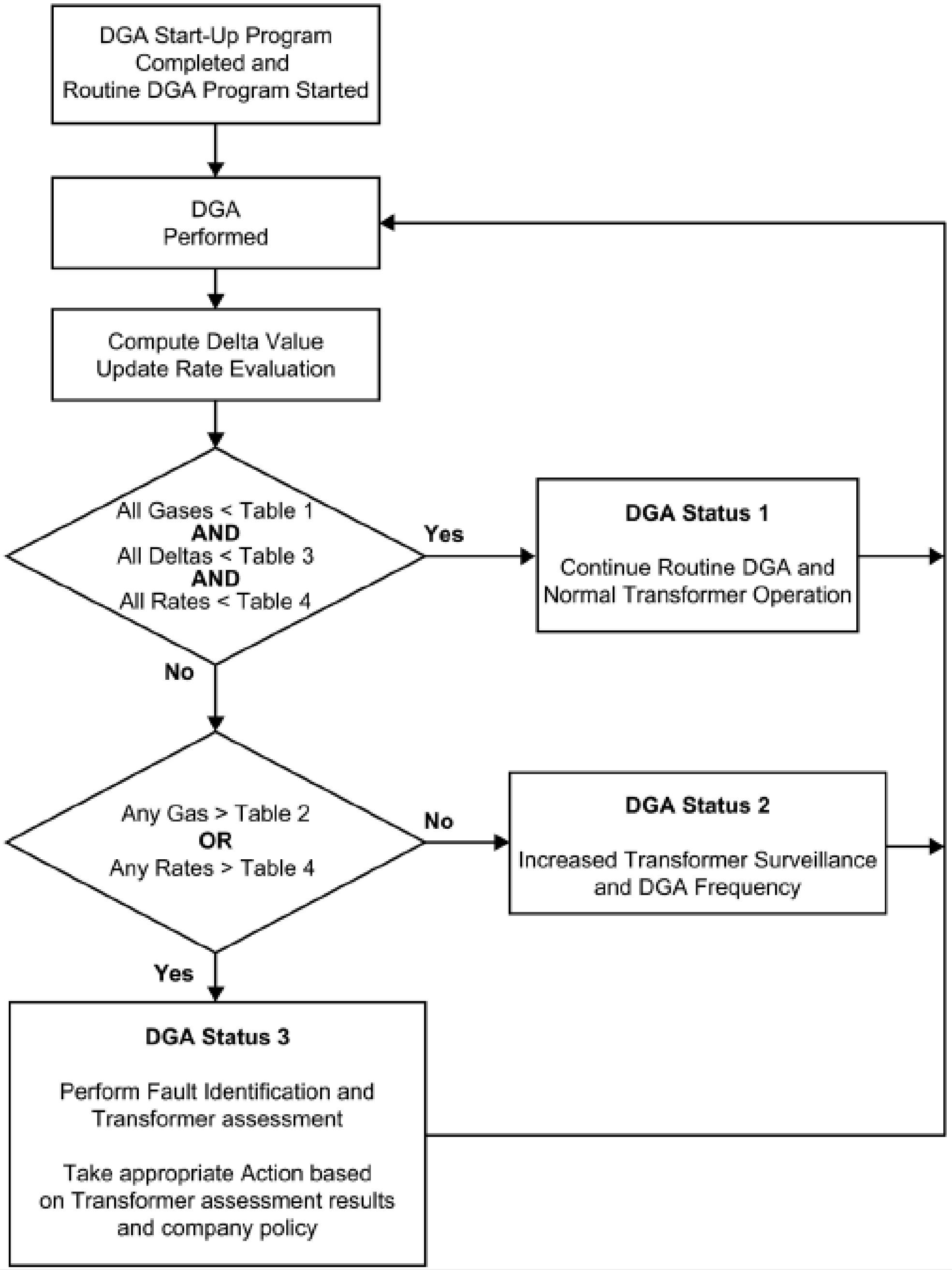
- Analysis of these gases and their interpretation is an art
- Variability in the interpretation depends on:
  - Type/brand/geometry of the transformer
  - Fault temperatures
  - Solubility and degree of saturation of various gases in oil
  - Type of oil preservation system
  - Type and rate of oil circulation
  - Types of materials in contact with oil
  - Sampling and measuring processes themselves
  - Lack of trend data
  - Residual gas from past events
  - Insufficient gas concentration to use for analysis

Interpretation of DGA Results *(cont.)*

Interpretation methods by which faults can be detected:

- IEEE C57.104-2008
- Key Gas Analysis
- Roger's Ratios
- Doernenburg's State Estimation
- Duval's Triangle

Interpretation of DGA Results – IEEE C57.104



Interpretation of DGA Results – IEEE C57.104

Table 1—90th percentile gas concentrations as a function of O_2/N_2 ratio and age in μL/L (ppm)

		O_2/N_2 Ratio ≤ 0.2				O_2/N_2 Ratio > 0.2			
		Transformer Age in Years				Transformer Age in Years			
		Unknown	1 – 9	10 – 30	>30	Unknown	1 – 9	10 – 30	>30
Gas	Hydrogen (H_2)	80	75		100	40	40		
	Methane (CH_4)	90	45	90	110	20	20		
	Ethane (C_2H_6)	90	30	90	150	15	15		
	Ethylene (C_2H_4)	50	20	50	90	50	25	60	
	Acetylene (C_2H_2)	1	1			2	2		
	Carbon monoxide (CO)	900	900			500	500		
	Carbon dioxide (CO_2)	9000	5000	10000		5000	3500	5500	

NOTE—During the data analysis, it was determined that voltage class, MVA, and volume of mineral oil in the unit did not contribute in significant way to the determination of values provided in Table 1.

Interpretation of DGA Results – IEEE C57.104

Table 3— 95th percentile values for absolute level change between successive laboratory DGA samples in µL/L (ppm)

		Maximum µL/L (ppm) variation between consecutive laboratory DGA samples	
		O_2/N_2 Ratio ≤ 0.2	O_2/N_2 Ratio > 0.2
Gas	Hydrogen (H_2)	40	25
	Methane (CH_4)	30	10
	Ethane (C_2H_6)	25	7
	Ethylene (C_2H_4)	20	
	Acetylene (C_2H_2)	Any Increase	
	Carbon monoxide (CO)	250	175
	Carbon dioxide (CO_2)	2500	1750

NOTE—Contribution of voltage class, MVA, and volume of mineral oil in the unit was not studied for Table 3 as they have not been retained for Table 1 and Table 2. Data was insufficient to study age influence.

Interpretation of DGA Results – IEEE C57.104

Table 4—95th percentile values from multi-points (3-6 points) rate analysis of laboratory DGA samples with all gas levels below Table 1 values, in µL/L/year (ppm/year)

		Maximum µL/L/year (ppm/year) rate in function of the period between first and last point of the laboratory DGA series (3 to 6 samples)			
		O_2/N_2 Ratio ≤ 0.2		O_2/N_2 Ratio > 0.2	
		Period between first and last point of the series			
		4-9 Months	10-24 Months	4-9 Months	10-24 Months
Gas	Hydrogen (H_2)	50	20	25	10
	Methane (CH_4)	15	10	4	3
	Ethane (C_2H_6)	15	9	3	2
	Ethylene (C_2H_4)	10	7	7	5
	Acetylene (C_2H_2)	Any increasing rate		Any increasing rate	
	Carbon monoxide (CO)	200	100	100	80
	Carbon dioxide (CO_2)	1750	1000	1000	800

NOTE—Contribution of voltage class, MVA, and volume of mineral oil in the unit was not studied for Table 4 as they have not been retained for Table 1 and Table 2. Data was insufficient to study age influence.

Interpretation of DGA Results – Key Gas Analysis

Each ‘Key Gas’ is identified with a certain fault

Fault Pattern	Key Gas
Conductor Overheating	CO/CO2 (Carbon Oxides)
Oil Overheating	C2H4 (Ethylene)
Partial Discharge	H2 (Hydrogen)
Arcing	C2H2 (Acetylene)

Examples:

Sl No	Fault	Principle gas	CO	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
1	Overheated oil	Ethylene C_2H_4	-	2%	16%	19%	63%	-
2	Overheated cellulose	Carbon monoxide CO	92%	-	-	-	-	-
3	Corona in oil	Hydrogen H_2	-	85%	13%	1%	1%	
4	Arcing in oil	Acetylene C_2H_2	-	60%	5%	2%	3%	30%

Interpretation of DGA Results – Roger's Ratio

- Method to determine fault based on relative concentrations of five gases:

  Hydrogen, Ethane, Ethylene, Methane and Acetylene

  – R1 = Acetylene/Ethylene
  – R2 = Methane/Hydrogen
  – R3 = Ethylene/Ethane

- Code assigned based on relative ratios of above gases

- Set of code numbers defines one among eight faults

Interpretation of DGA Results – Roger's Ratio

Table 6. – Rogers Ratios for Key Gases

Code range of ratios		$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$	Detection limits and 10 x detection limits are shown below:
<0.1 0.1-1 1-3 >3		0 1 1 2	1 0 2 2	0 0 1 2	C_2H_2 1 ppm 10 ppm C_2H_4 1 ppm 10 ppm CH_4 1 ppm 10 ppm H_2 5 ppm 50 ppm C_2H_6 1 ppm 10 ppm
Case	**Fault Type**				**Problems Found**
0	No fault	0	0	0	Normal aging
1	Low energy partial discharge	1	1	0	Electric discharges in bubbles, caused by insulation voids or super gas saturation in oil or cavitation (from pumps) or high moisture in oil (water vapor bubbles).
2	High energy partial discharge	1	1	0	Same as above but leading to tracking or perforation of solid cellulose insulation by sparking, or arcing; this generally produces CO and CO_2.
3	Low energy discharges, sparking, arcing	1-2	0	1-2	Continuous sparking in oil between bad connections of different potential or to floating potential (poorly grounded shield etc); breakdown of oil dielectric between solid insulation materials.
4	High energy discharges, arcing	1	0	2	Discharges (arcing) with power follow through; arcing breakdown of oil between windings or coils, or between coils and ground, or load tap changer arcing across the contacts during switching with the oil leaking into the main tank.
5	Thermal fault less than 150 °C (see note 2)	0	0	1	Insulated conductor overheating; this generally produces CO and CO_2 because this type of fault generally involves cellulose insulation.
6	Thermal fault temp. range 150-300 °C (see note 3)	0	2	0	Spot overheating in the core due to flux concentrations. Items below are in order of increasing temperatures of hot spots. Small hot spots in core. Shorted laminations in core. Overheating of copper conductor from eddy currents. Bad connection on winding to incoming lead, or bad contacts on load or no-load tap changer. Circulating currents in core; this could be an extra core ground, (circulating currents in the tank and core); this could also mean stray flux in the tank. These problems may involve cellulose insulation which will produce CO and CO_2.
7	Thermal fault temp. range 300-700 °C	0	2	1	
8	Thermal fault temp. range over 700 °C (see note 4)	0	2	2	

Interpretation of DGA Results – Doernenburg's State of Estimation

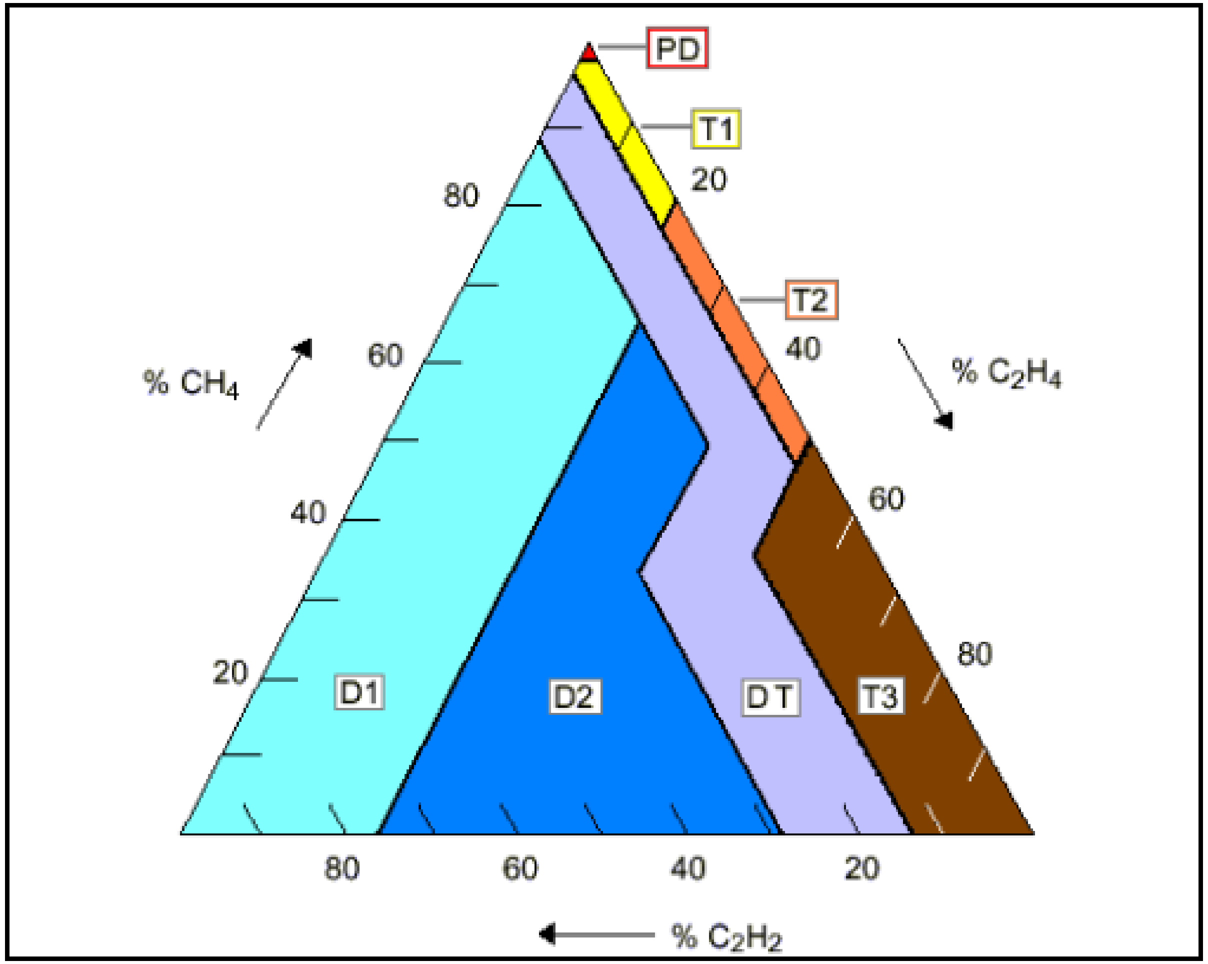
- Similar to Roger's ratios but with four ratios instead of three
  - Ratio 1: Methane/Hydrogen
  - Ratio 2: Acetylene/Ethylene
  - Ratio 3: Acetylene/Methane
  - Ratio 4: Ethane/Acetylene

Indicated Fault Diagnosis	Ratio 1	Ratio 2	Ratio 3	Ratio 4
Thermal Decomposition	0.1- 1.0	0.75 – 1.0	0.1 – 0.3	0.2 – 0.4
Corona	0.01 – 0.1	Not significant	0.1 – 0.3	0.2 – 0.4
Arcing	0.1 – 1.0	0.75 – 1.0	0.1 – 0.3	0.2 – 0.4

Interpretation of DGA Results – Duval’s Triangle and Pentagons

- Developed using a database of thousands of DGAs and transformer problem diagnoses
- This method describes 6 basic fault types
  - PD = Partial Discharge
  - T1 = Thermal fault < 300C
  - T2 = Thermal fault between 300C to 700C
  - T3 = Thermal fault > 700C
  - D1 = Low energy discharge (Sparking)
  - D2 = High energy discharge (Arcing)
  - DT = Mix of thermal and electrical faults

Interpretation of DGA Results – Duval's Triangle



$$\%CH_4 = \frac{CH_4}{CH_4 + C_2H_2 + C_2H_4} \times 100$$

$$\%C_2H_2 = \frac{C_2H_2}{CH_4 + C_2H_2 + C_2H_4} \times 100$$

$$\%C_2H_4 = \frac{C_2H_4}{CH_4 + C_2H_2 + C_2H_4} \times 100$$

Advantages of DGA

- Dissolved gases are detectable in low concentration levels (parts per million - ppm)
- Advanced warning of incipient faults
- Status checks on new or repaired units
- Convenient scheduling of repairs
- Monitoring of units under overload
- Information about fault can reduce equipment downtime
- Helps to make a prognosis on the life of a transformer
- Information to perform root-cause analysis after a failure has occurred

Disadvantages of DGA

- DGA cannot detect location of a fault
- Preventing acute faults which develop within seconds or minutes
- Insulation degradation caused by elevated temperatures (<150 C) for a long time
- If the transformer has been refilled with fresh oil, results may not be indicative of faults

Considerations for Transformer Users

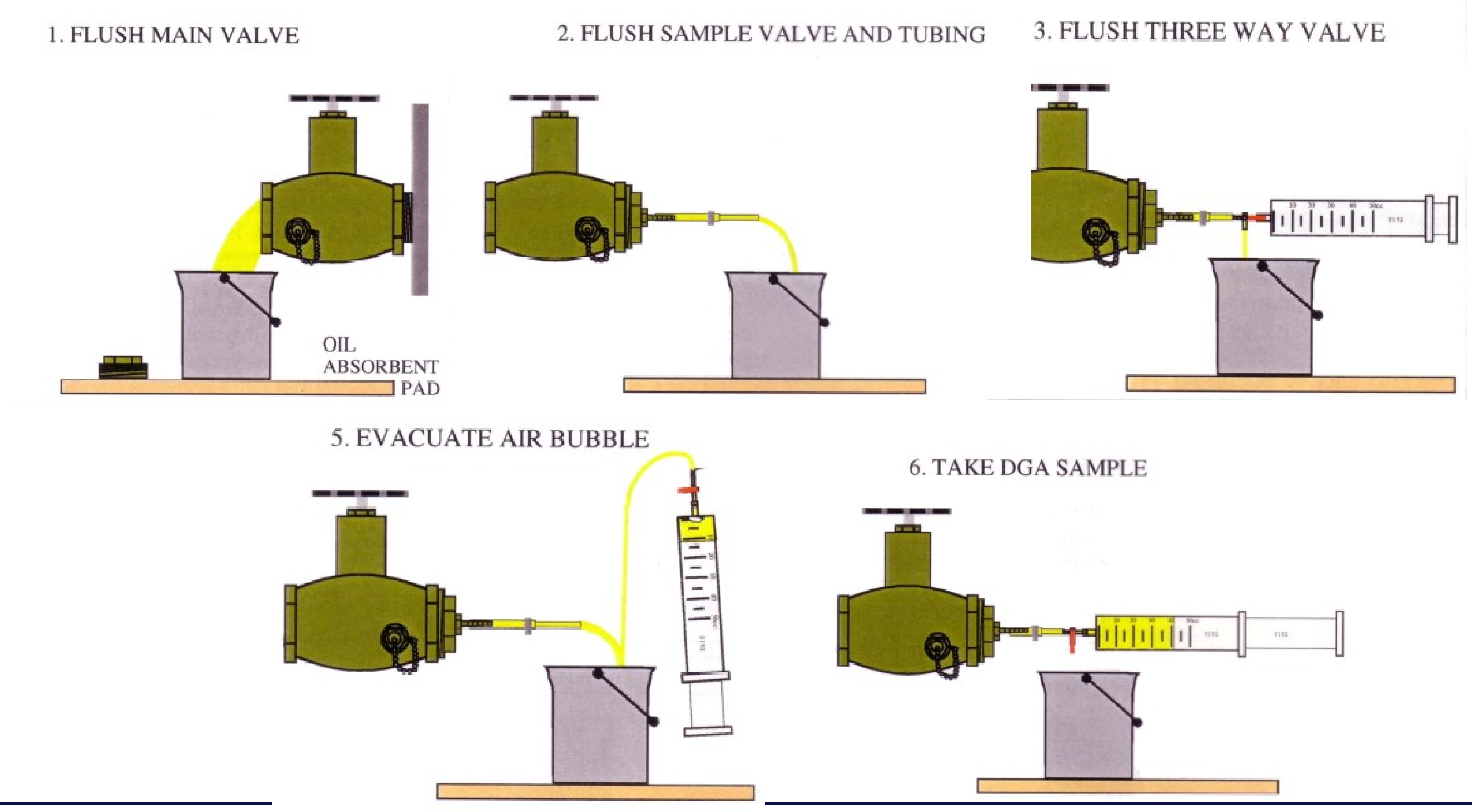
- Interpretation is an art, consider the factors which lead to the variability in analysis
- Residual gases in the oil from previous faults might lead to misleading interpretations
- More critical the unit, more frequently it should be sampled
- There are no standard levels of concern/action levels of gas concentration, different companies have their own levels
- As key gas concentrations approach the action levels, consideration should be given to taking the transformer out of service for further testing and inspection
- Consider 'online' monitoring as some monitors do much of the analysis for you.

Considerations for Transformer Users *(cont.)*

Factors affecting effectiveness of DGA

- Use only trained and qualified people to take oil (or gas) samples
- Carefully select a laboratory for the analysis
- Compare transformers on an equal oil volume basis
- Establish a base line measurement for each transformer
- Establish a sampling plan to generate trend data
- Repeat sampling and analysis to confirm the diagnosis before taking drastic action on a single sample

How to Take a DGA Sample



Example: Other Oil Diagnostics

WEIDMANN

WEIDMANN ELECTRICAL TECHNOLOGY
3430 PROGRESS DRIVE, UNIT B + BENSALEM, PA + 19020
215 639 8599 + 215 639 8577
WWW.WEIDMANN-DIAGNOSTICS.COM

TEST REPORT
01-6794494-478216-00

SPX Transformer Solutions Inc	**Serial#:**	RISING SUN	**Mfr:**	ABB	**Control#:**	6794494
2701 US HWY 117 SOUTH	**Location:**	RISING SUN	**kV:**		**Order#:**	478216
	Equipment:	TRANSFORMER	**kVA:**		**Account:**	1371
GOLDSBORO, NC 27530 US	**Compartment:**	MAIN(BOTTOM)	**Year Mf'd:**		**Received:**	06/19/2015
ATTN: SAMUEL CAUDILL	**Breathing:**	SEAL	**Syringe ID:**	V372	**Reported:**	07/07/2015
PO#: 121775-002	**Bank:**	**Phase:**	**Bottle ID:**			
Project ID:	**Fluid:**	MIN	**Sampled By:**			
Customer ID: PCL						

	Lab Control Number:	6794494
	Date Sampled:	06/18/2015
	Order Number:	478216
	Oil Temp:	
PER IEEE C57.106-2006	**Interfacial Tension:**	Acceptable for equipment >= 230 kV for in-service oil - kV not provided (32 dynes/cm min).
(most recent sample)	**Acid Number:**	Acceptable for equipment >= 230 kV for in-service oil - kV not provided (0.1 mg KOH/g max).
	Color Number and Visual:	Diagnostic not applicable. Diagnostic not applicable.
	Dielectric Breakdown D-877:	Diagnostic not applicable.
	Power Factor @25C:	Acceptable for equipment >= 230 kV for in-service oil - kV not provided (0.5% max).
	Oxidation Inhibitor:	Diagnostic not applicable for type 1 oil. Acceptable for in-service oil type 2 (0.09% min).

Comment:

Corrosive Sulfur in Oil	**ASTM Test Method**	**Classification**	**Result**
(most recent sample)	**D-1275B**	1A	Non-Corrosive

Comment:

Furanic Compound	**2-Furaldehyde (ppb):**	69
D-5837[5]	**5-Hydroxy-methyl-furaldehyde (ppb):**	< 10
	2-Acetylfuran (ppb):	< 10
	5-Methyl-2-furaldehyde (ppb):	21
	2-Furyl alcohol (ppb):	< 10

Furanic Compound Diagnostics (most recent sample):

New insulation with a high degree of mechanical strength will typically have a Degree of Polymerization (DP) of 1000-1300. "Middle Aged" paper is approximately 500 and paper with less than 250 is in its "Old Age." Severely degraded insulation with a DP of 150 or less will have very little mechanical strength and may result in a transformer failure. The above estimations are based on a study by Chendong of GSU transformers filled with mineral oil.

Estimated Average Degree of Polymerization (DP): 763

Estimated Operating Age of the Equipment: 11.5

Notations:

Comment:

Metals	**Silver (Ag) (ppm):**	< 0.5
Dissolved	**Aluminum (Al) (ppm):**	< 0.5
Fault, Wear and	**Barium (Ba) (ppm):**	< 0.5
Contamination	**Boron (B) (ppm):**	< 0.5
D-7151[5]	**Calcium (Ca) (ppm):**	< 0.5
	Chromium (Cr) (ppm):	< 0.5
	Copper (Cu) (ppm):	< 0.5
	Sodium (Na) (ppm):	< 0.5
	Iron (Fe) (ppm):	< 0.5
	Magnesium (Mg) (ppm):	< 0.5
	Molybdenum (Mo) (ppm):	< 0.5
	Nickel (Ni) (ppm):	< 0.5
	Phosphorus (P) (ppm):	< 0.5
	Lead (Pb) (ppm):	< 0.5
	Silicon (Si) (ppm):	< 0.5
	Tin (Sn) (ppm):	< 0.5
	Vanadium (V) (ppm):	< 0.5
	Zinc (Zn) (ppm):	< 0.5

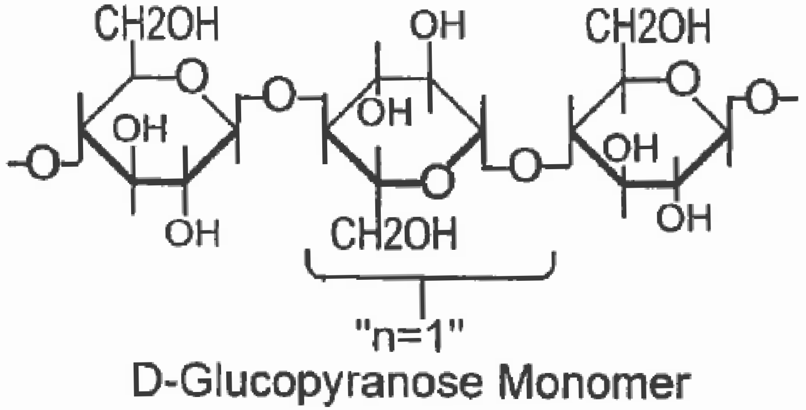
Comment:

Notations: 1. Analysis is ISO/IEC 17025:2005 accredited, L-A-B Accredited Certificate Number L2303.02 2. This test is conducted by a subcontracted laboratory. 3. Subcontracted laboratory has received ISO Standard 17025 accreditation for this test. 5. This test is conducted by Weidmann Laboratory other than Primary Lab. 6. Weidmann Laboratory has received ISO Standard 17025 accreditation for this test. 7. Imported Sample: WEIDMANN Electrical Technology accepts no responsibility for these results; accreditation status does not apply to these results. 8. Imported Equipment

Furans

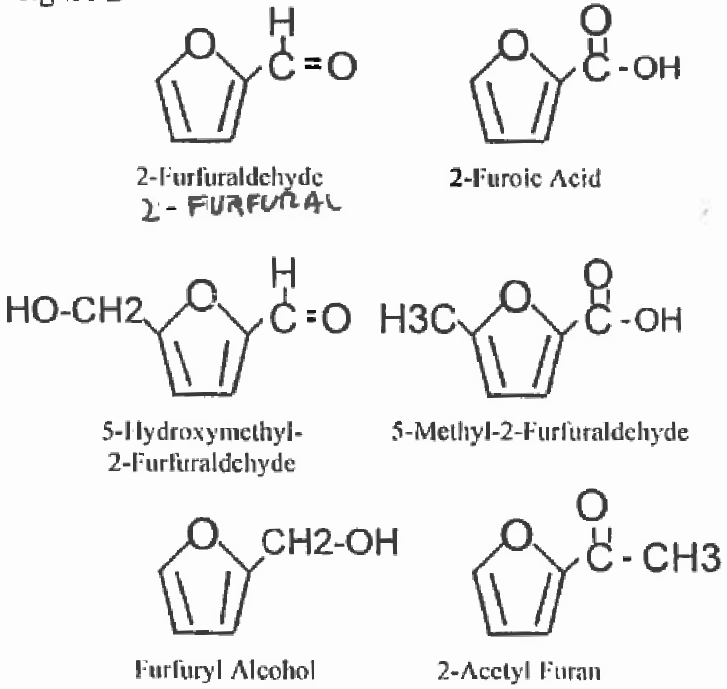
A Portion of the Insulation Molecule

figure 1



Cellulose Decomposition Compounds Found in Oil

figure 2



Furans

Most analytical Labs determine the concentration of five Furanic compounds:

Compound	**Abbreviation**	**Cause**
2-furaldehyde	(2FAL)	General overheating, normal ageing.
5-methyl-2-furaldehyde	(5M2F)	High Temperatures
5-hydroxylmethyl-2-furaldehyde	(5H2F)	Oxidation
2-acetyl furan	(2ACF)	Rare, causes not fully identified
2-furfuryl alcohol	(2FOL)	High Moisture

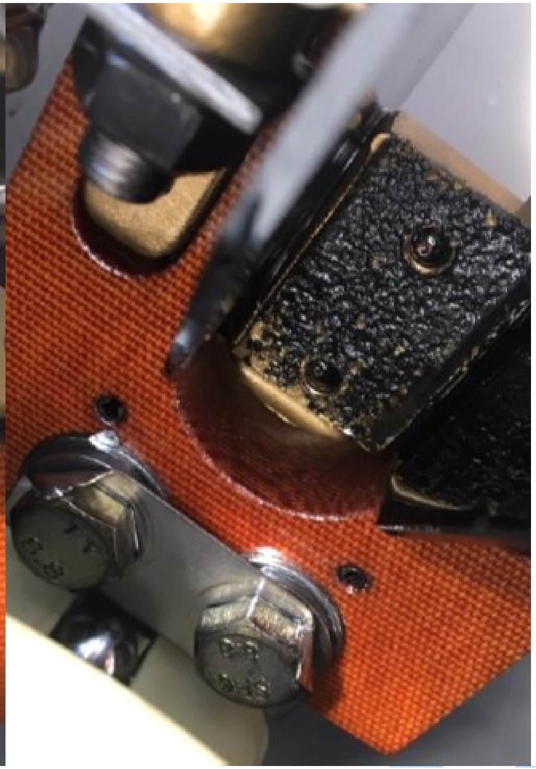
Note: *2FAL is stable for years while other Furanic compounds are less stable. They tend to form and then degrade to 2FAL over a period of months.*

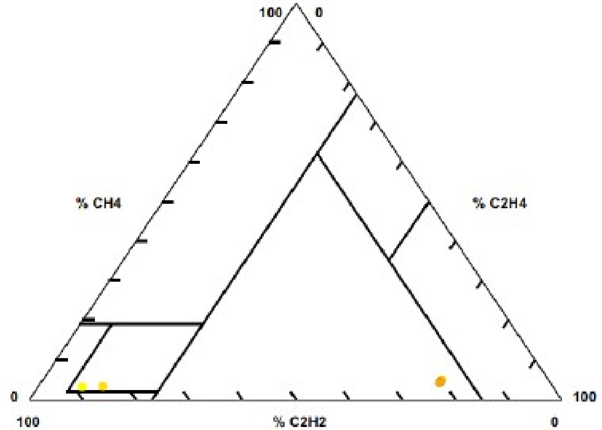
DGA Fault Example (Ester Fluid)

Dissolved Gas Analysis The dissolved gas analysis is run in accordance with ASTM D 3612 and IEC 60567. Values are reported in ppm vol/vol at STP and calibrated with gas-in-oil standards. Values before August 15, 2002 are reported at NTP and calibrated with gas standards.																
Report #	**Sample Date**	**Top Oil Temp °C**	**Hydrogen (H2)**	**Oxygen (O2)**	**Nitrogen (N2)**	**Methane (CH4)**	**Carbon Monox. (CO)**	**Ethane (C2H6)**	**Carbon Dioxide (CO2)**	**Ethylene (C2H4)**	**Acetylene (C2H2)**	**Total Gas**	**COMB GAS**	**EST TCG %**	**C2H4/ C2H2**	**Comb Gas Rate**
																ppm/day
122357	**10/15/2012**	**24**	**58**	**339**	**68100**	**3.0**	**35**	**15**	**143**	**9.3**	**18**	**68720**	**138**	**0.20**	**0.52**	**0.33**
113052	05/10/2012	25	45	524	65700	0.6	33	7.0	116	0	0	66426	86	0.16	0.00	0.00
106288	08/16/2011	25	46	72	64700	0.7	30	8.8	116	0	0	64974	86	0.16	0.00	0.06
95180	02/03/2010	20	26	3060	63400	0	21	5.3	104	0	0	66616	52	0.10	0.00	0.06
91504	07/13/2009	35	18	2490	60900	0	17	4.4	104	0	0	63533	39	0.07	0.00	
INVESTIGATE Arcing in oil. Condition is severe.																

DGA Fault Example (LTC)

Sample ID	Col Date	Moisture	Acetylene	Hydrogen	CO	Ethylene	Ethane	Methane	T Comb	CO2	Nitrogen	Oxygen	Ethyl/Acety Ratio
AV25284	10/28/2015	0.0035	654.	53.	36	61.	ND	24.	828.	668	6.6	2.47	0.09
AW11121	5/2/2016	0.0021	475.	53.	25	68.	ND	19.	640.	629	6.8	2.96	0.14
AX04882	2/27/2017	0.0054	546.	33.	39	2046.	389.	137.	3190.	620	6.4	2.73	3.75
AX06034	3/14/2017	0.0014	570.	30.	11	2056.	414.	118.	3199.	606	6.4	3.16	3.61





% CH4	% C2H4	% C2H2	Fault	Color	Date
3.2	8.3	88.5	N		10/28/2015 0:00
3.4	12.1	84.5	N		5/2/2016 0:00
5.0	75.0	20.0	X3		2/27/2017 0:00
4.3	74.9	20.8	X3		3/14/2017 0:00