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Techniques for Interpretation of Data for DGA From Transformers and Case Studies

Doble Engineering



Purpose of DGA



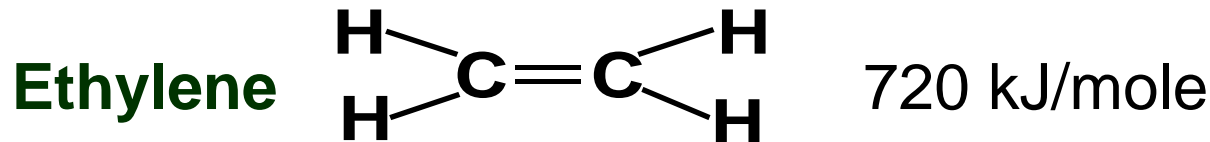
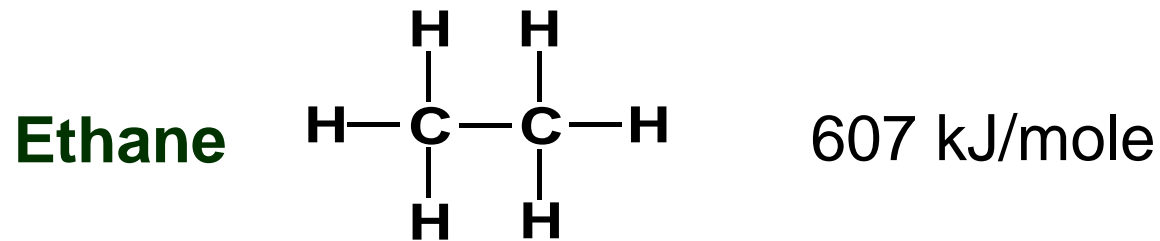
- To provide a non-intrusive means to determine if a transformer incipient fault condition exists or not
 - Too conservative
 - Too liberal
 - To have a high probability that when entering an transformer a problem is apparent
 - To prevent an unexpected outage
 - To reduce risk to the unit and the system/company
-



Energy Required to Break Bonds and Form Gases



Various gasses are created during oil decomposition depending on the type of fault



Gases Detected



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Gas	Type
Hydrogen	
Oxygen	
Nitrogen	
Methane	Hydrocarbon
Carbon Monoxide	
Ethane	Hydrocarbon
Carbon Dioxide	
Ethylene	Hydrocarbon
Acetylene	Hydrocarbon

Other gases can be detected but are not used in the routine analysis



Total Combustible Gases, TCG



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Gas	Type
Hydrogen	
Methane	Hydrocarbon
Carbon Monoxide	
Ethane	Hydrocarbon
Ethylene	Hydrocarbon
Acetylene	Hydrocarbon

Other gases can be detected but are not used in the routine analysis



Generation Temperatures



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Gas	Temp
Hydrogen	≈ 120°C
Methane	≈ 120°C
Ethane	≈ 150°C
Ethylene	≈ 300°C
Acetylene from overheating	≈ 700°C
Acetylene from arcing	≈ 1200°C

In oil only, does not include the effects of paper

Other gases can be detected but are not used in the routine analysis

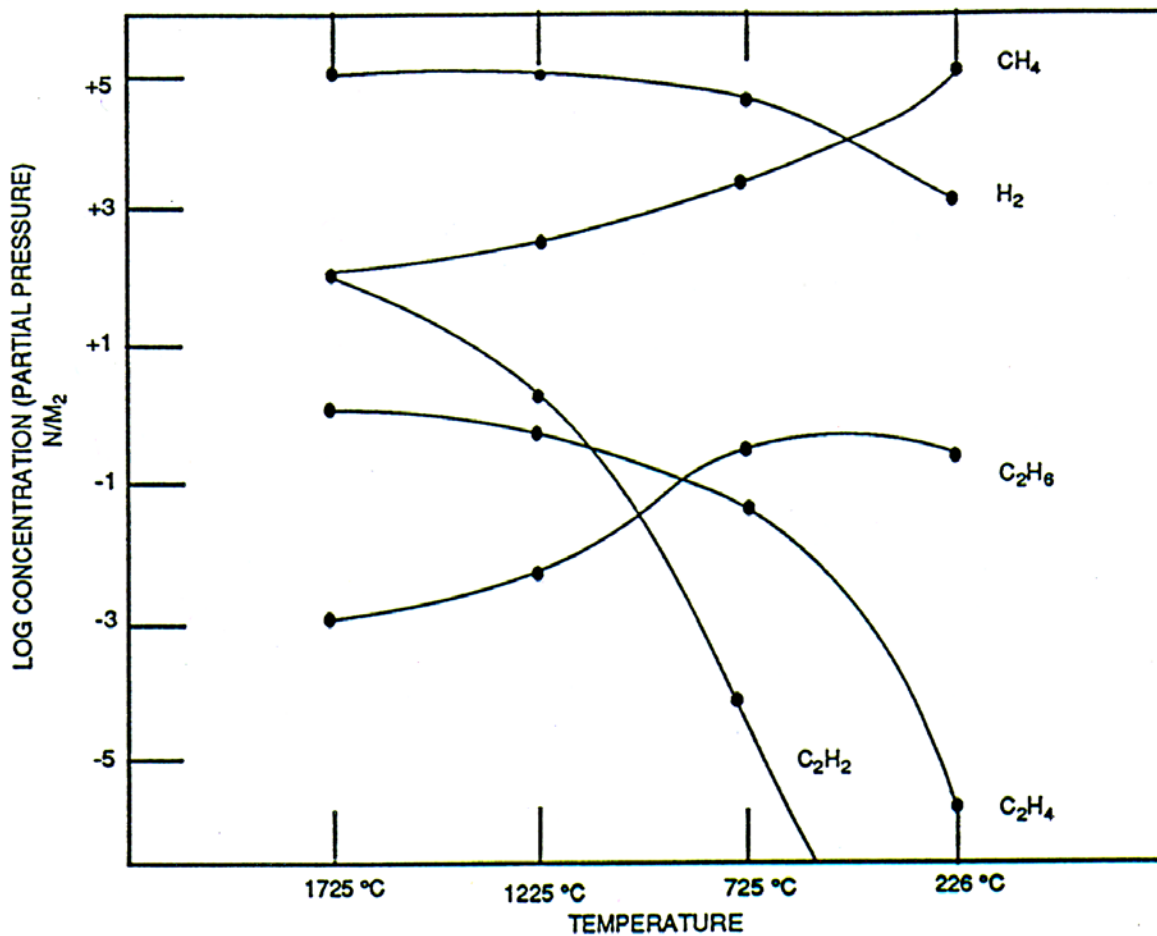


Halstead's Thermal Equilibrium



IEEE
Std C57.104-1991

IEEE GUIDE FOR THE INTERPRETATION OF GASES



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Dissolved Gas Analysis - 3 Methods



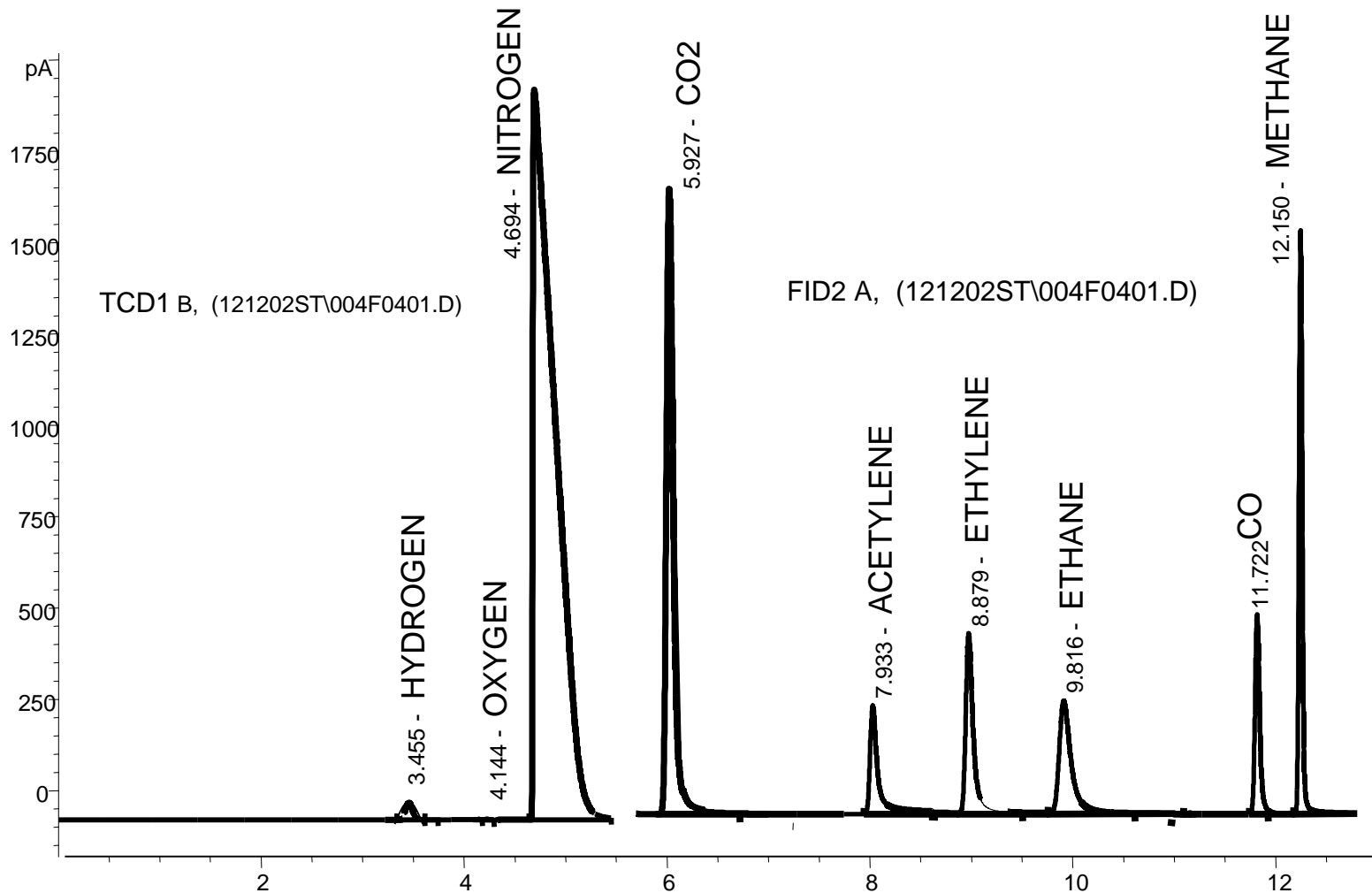
- Method A - Vacuum extraction/GC Analysis
 - Method B - Stripper Column/GC Analysis
 - Method C - Headspace/GC Analysis
-



Standard Gas - Gas Chromatogram



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Impact of Preservation System



- Standard Gas Sealed Tank Design
 - Automatic Gas Control Sealed Design
 - Gas - Oil Sealed Design
 - Sealed Conservator with Membrane Design
 - Free Breathing Conservator Design
 - Gas Sealed Vs. Sealed Conservator w/
Membrane
-



Solubility of Gases in Oil



- Hydrogen, Carbon Monoxide, (Methane to lesser degree)
 - proportionally higher in closed conservator than gas blanketed
 - slowly lost to atmosphere in open conservator
 - Leak
-



Homogeneity of Gases in Oil



- Rate of generation
 - Access of fault area to flow
 - Rate of mixing
 - Presence of a gas blanket
 - Diffusion
-



Gas Bubbles



-
- Super-saturation of the oil with gas
 - Thermal decomposition of the cellulosic insulation
 - Vaporization of adsorbed moisture in the cellulose
-



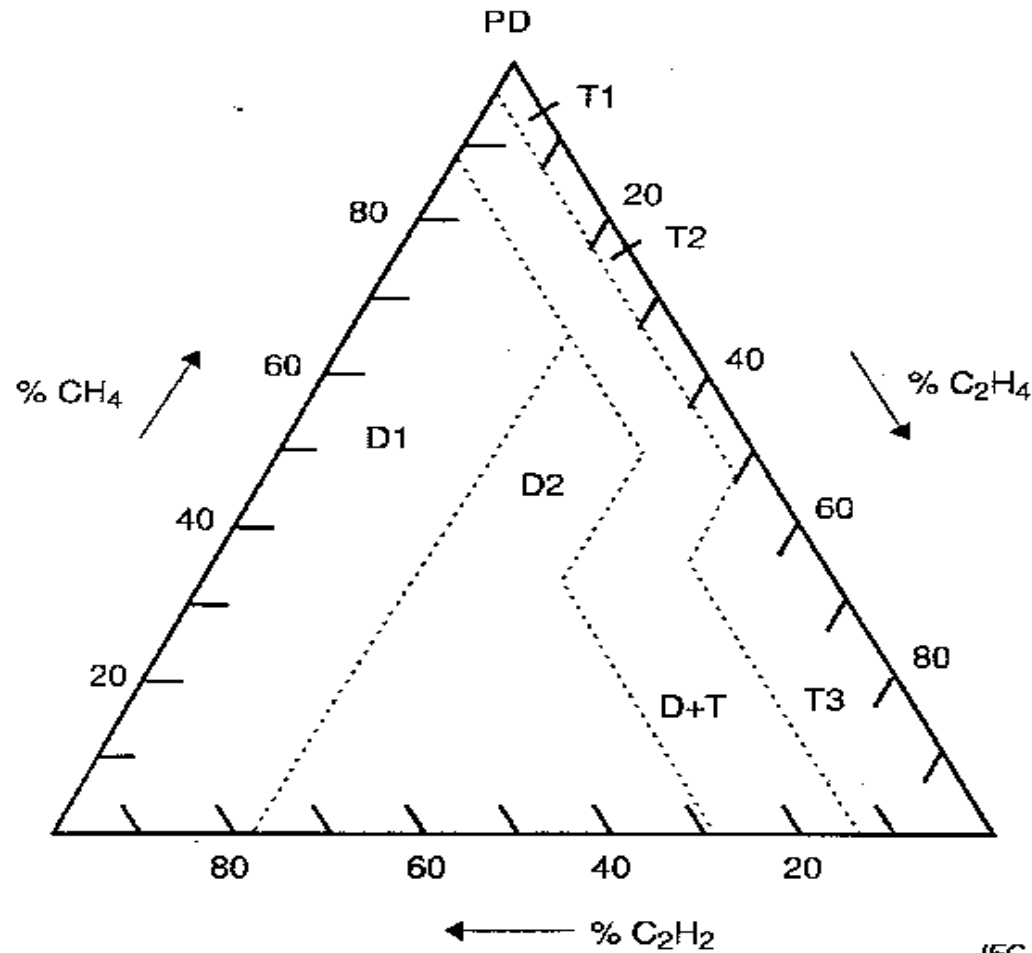
Most Commonly Used Interpretation Techniques



- Duval Triangle
 - IEEE C57.104, Limits, rates and TDCG
 - Straight Limits
 - Key Gas Method
 - Dörnenburg Ratios
 - Rogers Ratios
 - IEC 60599 Ratios and Limits
 - Trend Analysis
 - Fingerprints
 - Expert System Analysis
-



Duval Triangle



IEC 1 644/98



Key to Duval Triangle



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- Key**
- PD** Partial discharges
 - D1** Discharges of low energy
 - D2** Discharges of high energy
 - T1** Thermal fault, $t < 300^{\circ}\text{C}$
 - T2** Thermal fault, $300^{\circ}\text{C} < t < 700^{\circ}\text{C}$
 - T3** Thermal fault, $t > 700^{\circ}\text{C}$

Limits of zones

PD	98% CH₄			
D1	23% C₂H₄	13% C₂H₂		
D2	23% C₂H₄	13% C₂H₂	38% C₂H₂	29% C₂H₂
T1	4% C₂H₂	10% C₂H₄		
T2	4% C₂H₂	10% C₂H₄	50% C₂H₄	
T3	15% C₂H₂	50% C₂H₄		

Dissolved Gas Acceptable Limits Various Sources



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	H ₂	CO	CH ₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂	CO ₂	TCG
*IEEE	100 101-700 701-1800 >1800	350 351-570 571-1400 >1400	120 121-400 401-1000 >1000	65 66-100 101-150 >150	50 51-100 101-200 >200	35 36-50 51-80 >80	2500 2500-4000 4001-10000 >10000	720 721-1920 1921-4630 >4630
**Electra (CIGRE)	28.6	289	42.2	85.6	74.6	--	3771	520
IEC 60599 Typical Range	60-150	540-900	40-110	50-90	60-280	3-50	5100-13000	
Manufact.	200 (250)	500 (1000)	100 (200)	100 (200)	150 (300)	15 (35)	-- --	1065 1985

*IN THE PROCESS OF BEING REVISED

**CORRECTED VALUES 1978

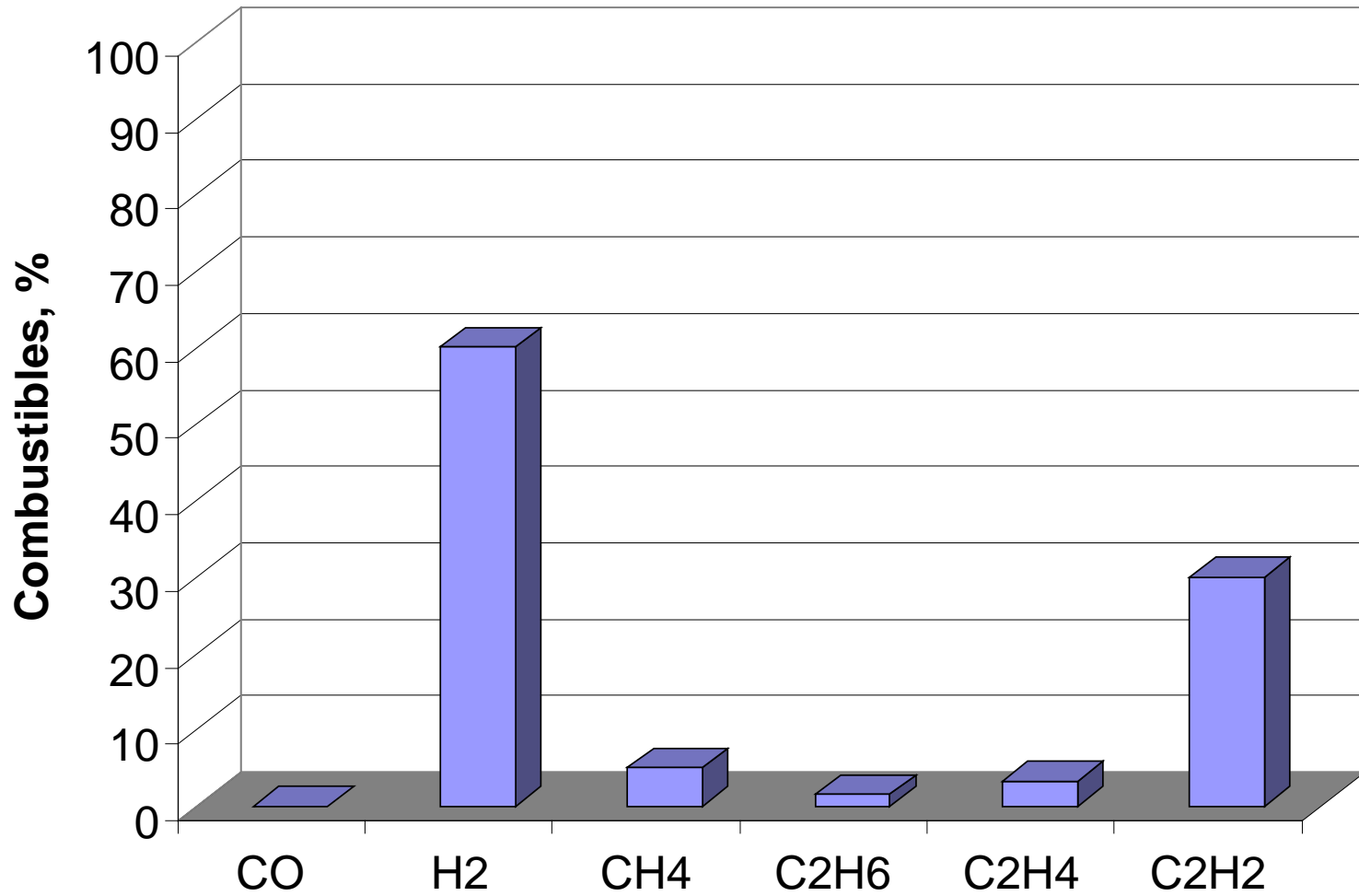
() VALUE 6 – 7 YEARS



Key Gases - Arcing



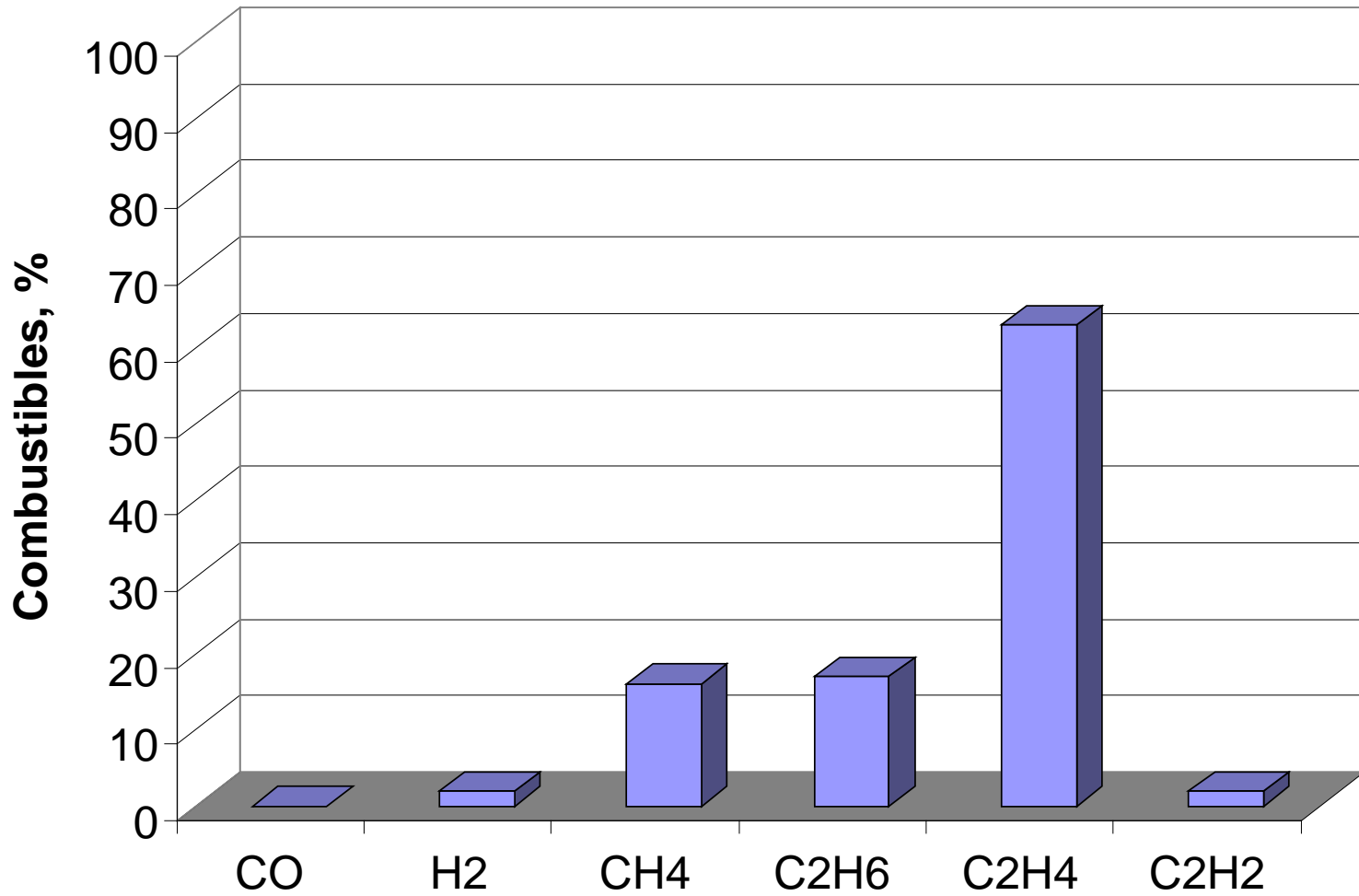
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Key Gases - Overheating, Oil



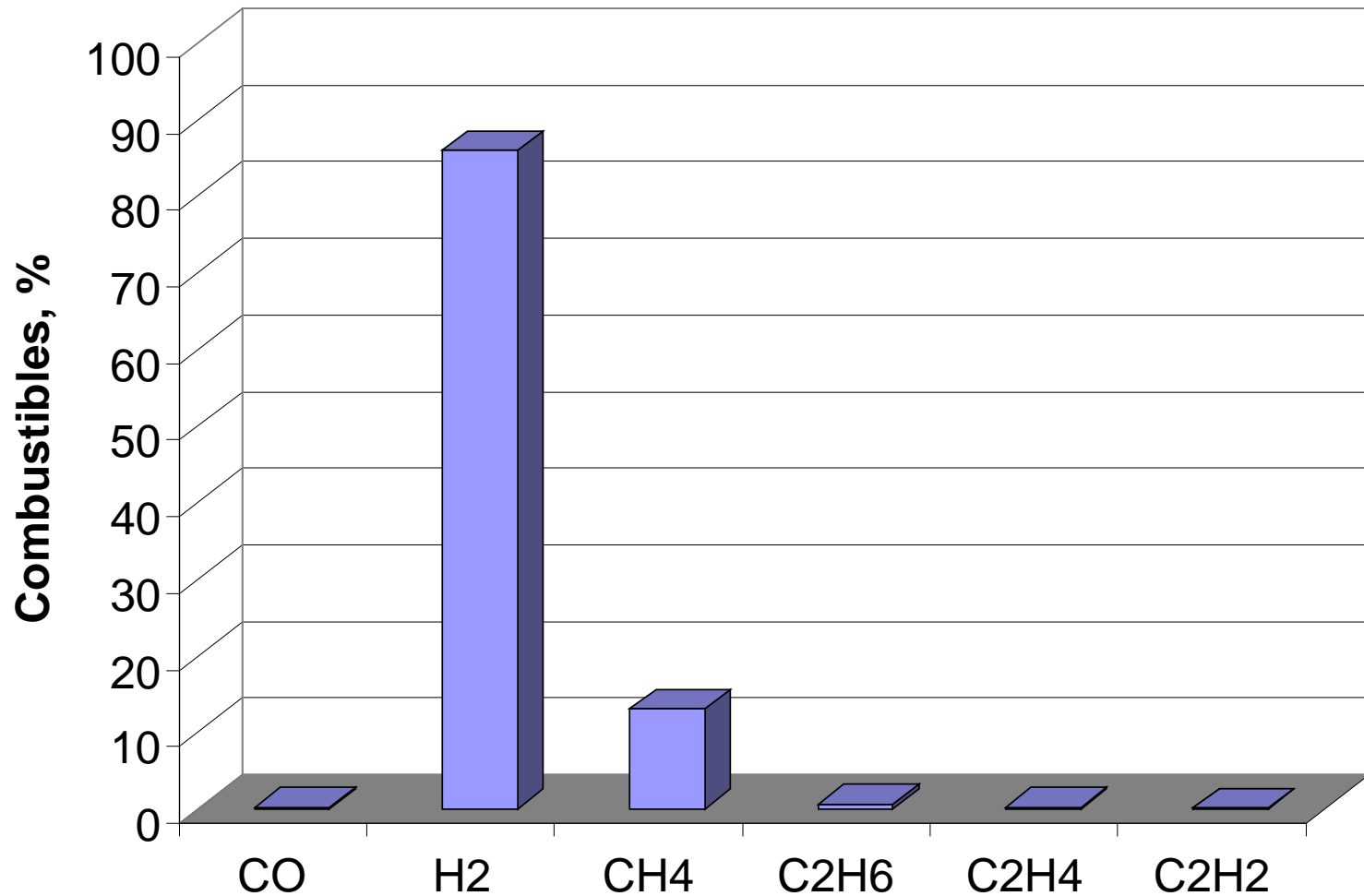
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Key Gases - Partial Discharge



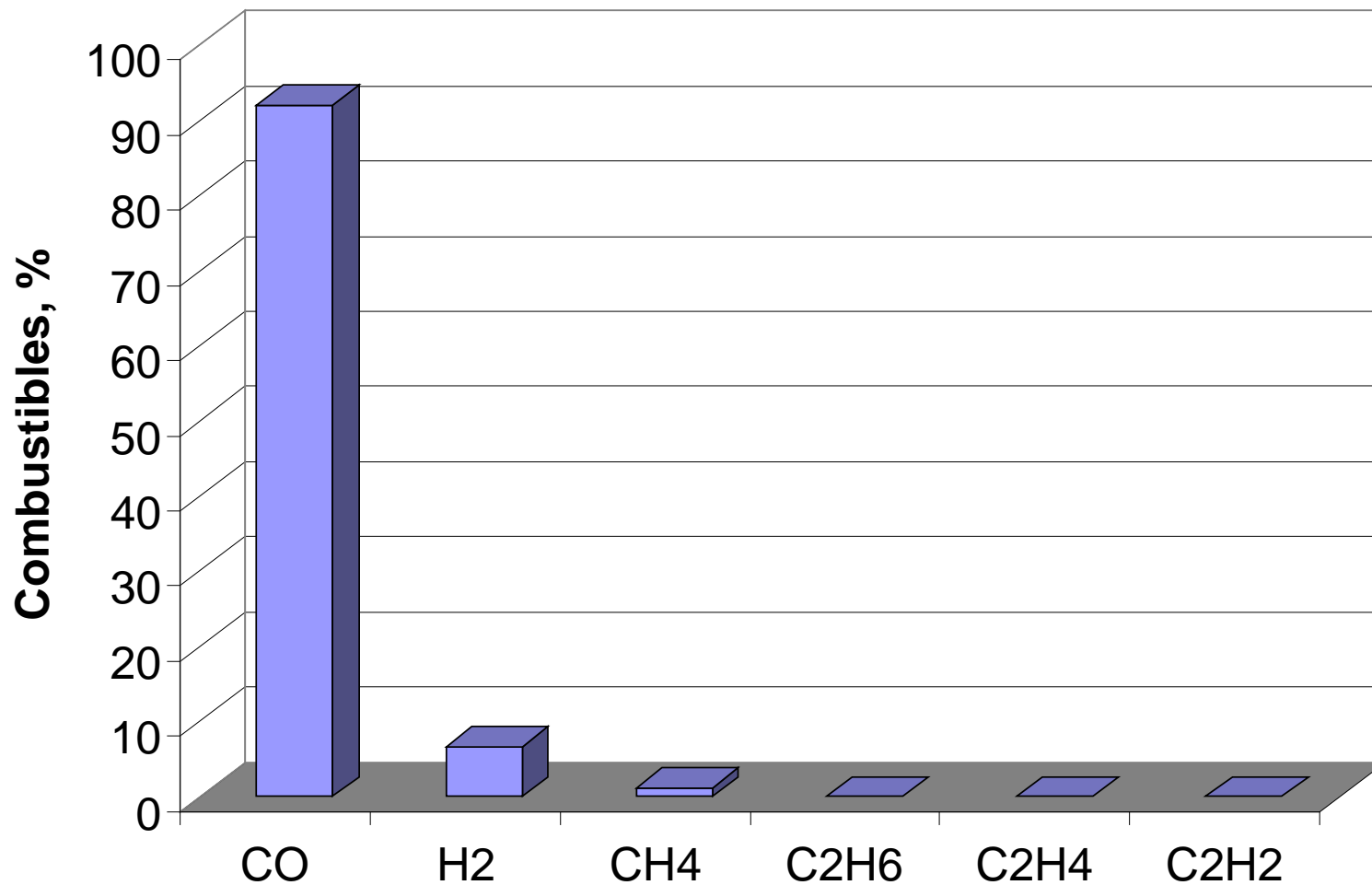
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Key Gases - Overheating, Paper



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Dörnenburg Ratio Method



- Ratio 1 (R1)= CH_4/H_2
 - Ratio 2 (R2)= $\text{C}_2\text{H}_2/\text{C}_2\text{H}_4$
 - Ratio 3 (R3)= $\text{C}_2\text{H}_2/\text{CH}_4$
 - Ratio 4 (R4)= $\text{C}_2\text{H}_6/\text{C}_2\text{H}_2$
-



Dörnenburg Ratio-Fault Diagnosis Table, from the oil



	R1 CH₄/H₂	R2 C₂H₂/C₂H₄	R3 C₂H₂/CH₄	R4 C₂H₆/C₂H₂
1-Thermal Decomp	>1.0	<0.75	<0.3	>0.4
2-Low Intensity PD	<0.1	Not Sig	<0.3	>0.4
3-Arcing	>0.1,<1.0	>0.75	>0.3	<0.4

Valid only if all the ratios for a particular fault type are met.



Roger's Ratio



- Three ratios
 - Ratio 1 (R1)= CH_4/H_2
 - Ratio 2 (R2)= $\text{C}_2\text{H}_2/\text{C}_2\text{H}_4$
 - Ratio 5 (R5)= $\text{C}_2\text{H}_4/\text{C}_2\text{H}_6$
- No minimum levels
 - suggested when normal levels exceeded



Roger's Ratio-Fault Diagnosis



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Case	R2 C_2H_2/C_2H_4	R1 CH_4/H_2	R5 C_2H_4/C_2H_6	Fault
0	<0.1	>0.1,<1.0	<1.0	Normal
1	<0.1	<0.1	<1.0	Low energy PD
2	0.1-3.0	0.1-1.0	>3.0	Arcing
3	<0.1	>0.1<1.0	1.0-3.0	Low temp thermal
4	<0.1	>1.0	1.0-3.0	Thermal <700°C
5	<0.1	>1.0	>3.0	Thermal >700°C



- Identifies 6 different fault types
 - PD: Partial Discharge
 - D1: Discharge of low energy
 - D2: Discharge of high energy
 - T1: Thermal fault, $t < 300$ C
 - T2: Thermal fault, 300 C $< t < 700$ C
 - T3: Thermal fault, $t > 700$ C
- Uses a combination of ratios (based on Roger's Ratios), gas concentrations and rates of gas increase



IEC 60599 Typical Gas Levels



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	H₂	CO	CH₄	C₂H₆	C₂H₄	C₂H₂	CO₂
IEC 60599 Typical Range	60-150	540-900	40-110	50-90	60-280	3-50	5100-13000
Communi cating OLTC	75-150	400-850	35-130	50-70	110-250	80-270	5300-12000

Note in IEC 60599: Typical values are higher in sealed transformers than free breathing transformers



Ratio Methods



- Advantages
 - quantitative
 - independent of oil volume
 - can be computer programmed
- Disadvantages
 - don't always yield an analysis
 - not always correct
 - dependence of preservation system
 - Dornenburg has fallen out of favor - misses too many incipient faults
- Solid insulation handled separately using carbon monoxide and carbon dioxide ratios



Trend Analysis



- Historical Information
 - Has the percent TCG in the gas space risen suddenly?
 - Has the percent TCG in the oil risen suddenly?
 - Nameplate information
 - How old in the transformer?
-



Trend Analysis



- Did a bushing fail at some point?
 - Did the transformer fail previously?
 - If the unit has been repaired and was the oil filtered or degassed?
 - Is the unit heavily loaded or overloaded?
 - **Previous dissolved gas-in-oil test?**
-



Carbon Oxide Gases and Ratios

Cellulose Insulation

- Shell form $>$ CO₂ than core form - due to mass
 - Accidental CO₂
 - CO₂/CO : 3 -14:1
 - CO₂/CO Avg. 7:1
 - Approach 1 high temperature faults
 - High CO₂ with low CO-lack of cooling/general overheating
-



Regular Interpretation

techniques miss the following:



- Incipient Faults not really covered
 - production of hydrogen from overheated oil thin films on core laminations (>140 C)
 - Oxidation and thermal heating of the oil causing the production of CO and CO₂
 - Gases produced not as a result of incipient fault condition
 - Leaking between the tap changer and main tank
-



Regular Interpretation

techniques miss the following:



- Galvanic reactions (steel + water + O₂ = hydrogen production)
 - lower voltage transformers having higher CO and CO₂ values as a result of non-vacuum treatment, oxygen + heat
 - Welding producing acetylene and other gases
 - Out-gassing of paints, gaskets & polymers, usually CO and CO₂
-



Regular Interpretation

techniques miss the following:



- Stray gassing characteristics (highly refined oils \Rightarrow H₂)
 - Contaminants produce gases
 - Decomposition of additives such as passivators can produce gases as well (H₂ and CO₂)
-



Regular Interpretation

techniques miss the following:



- Water
 - free water+ core steel+heat = hydrogen + oxygen
 - wet cellulose under PD yields more hydrogen
 - Silicone compounds, organic polymers
 - under severe thermal and electrical discharge (arcing)
 - hydrogen and CO
-



In Reality - Expert Systems are Used



- History
- Key gases
- Ratios
- Fingerprints - similar populations
- Trend analysis
- Internal databases
- Total combustible gas
- Rate of gas generation
- A human expert

***Use the tools in
the toolbox, not
just one!!!***



Total Combustible Gas Limits (ppm)



TCG

0-500

LOW LEVEL OF GASSING

501-1500

**MODERATE DECOMPOSITION - ESTABLISH
TREND**

1501-2500

**HIGH LEVEL OF DECOMPOSITION -
ESTABLISH TREND**

>2500

**VERY HIGH LEVEL OF DECOMPOSITION
- IDENTIFY CAUSE**



Types of Thermal Problems



- Over excitation of core
 - No load tap changer
 - Turn-to-turn or strand-to-strand short
 - Unintentional core ground
 - Core-circulating currents
 - Stray flux
-



Types of Thermal Problems



- Geo-magnetically induced core saturation
 - Poor connection
 - Shield problem
 - Leak between main tank and tap changer compartment
 - Poor crimp connection
 - Bad pump
-



Other Diagnostic Tests



- Infrared Thermography - detect localized hot spots
 - Main Insulation Power Factor Tests - insulation degradation or deterioration, excessive water in cellulose structures
 - Exciting Current Tests (All LTC Positions if LTC Installed) - LTC problems, shorted turns, core problems
 - Turns Ratio Test - shorted turns
-



Other Diagnostic Tests



- Winding and core insulation resistance
 - Test for unintentional core ground
 - Leakage reactance/ short circuit impedance - winding deformation
 - Sweep Frequency Response Analysis - winding deformation or movement, shorted turns
 - Partial Discharge - acoustic and electrical
-



Operating Conditions



- Loading
 - Thermal performance
 - Functional components and dielectric materials
-



What to do When a Problem is Identified



- Timing
 - Identify possible sources
 - Use other diagnostic tests
-



Dissolved Gas Analysis - Case Study 1



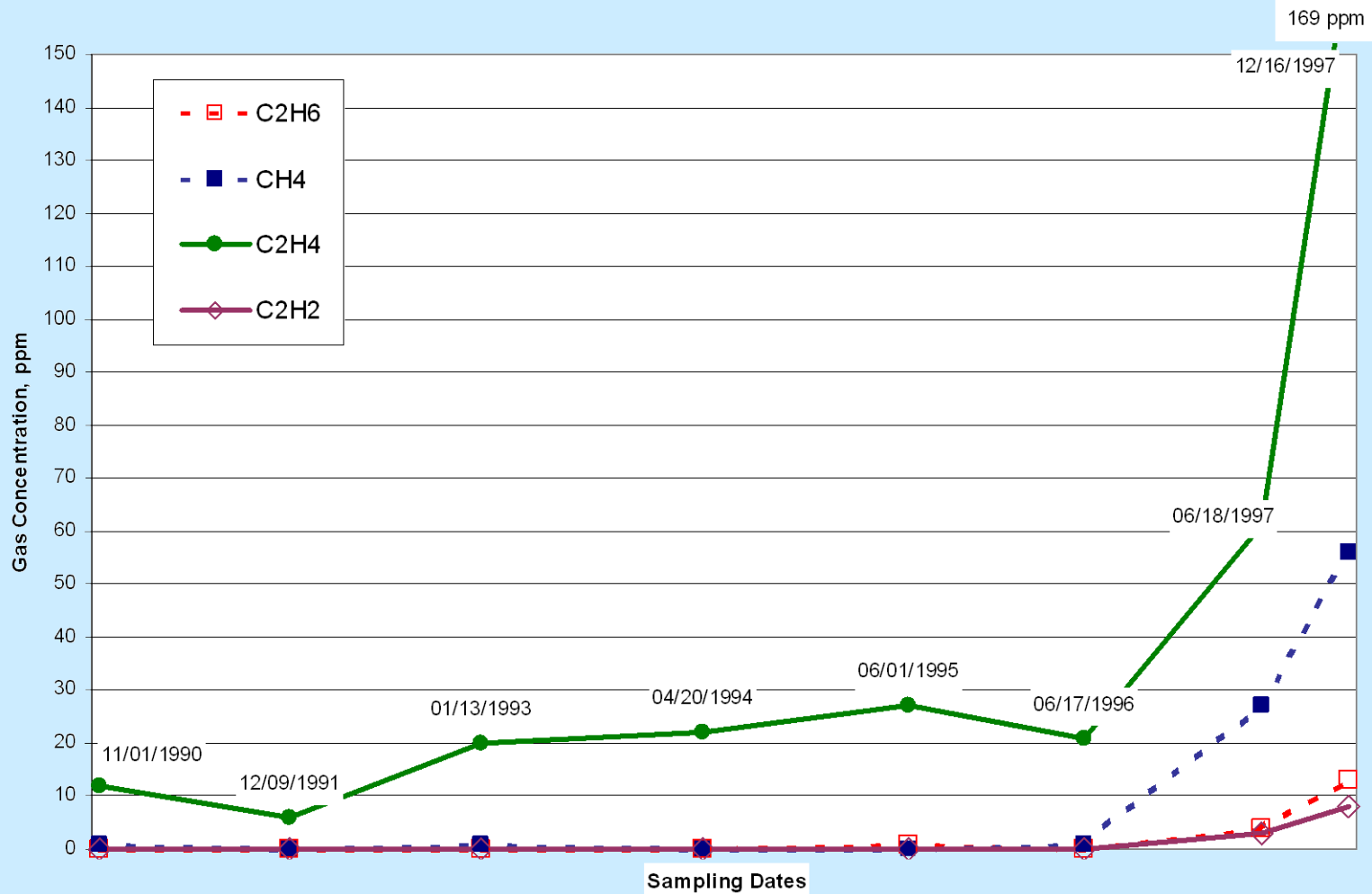
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- Manufacturer Ferranti Packard
 - Year 1969
 - Estimated Service Time 30 Years
 - kV 34
 - MVA 18.5
 - Preservation System Free-breathing conservator
 - Failed No
 - Other Furnace XFMR
-



DGA Detects Incipient-Fault Condition in LTC



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Internal Inspection



- Found nothing in the transformer main tank
 - Inspection of LTC revealed two problems:
 - A pitted high voltage connector due to a poor connection
 - Compromised gasket was discovered, allowing oil from the LTC to enter the main tank
-



Pitted High Voltage Connector



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Case 2- Overheated Transformer



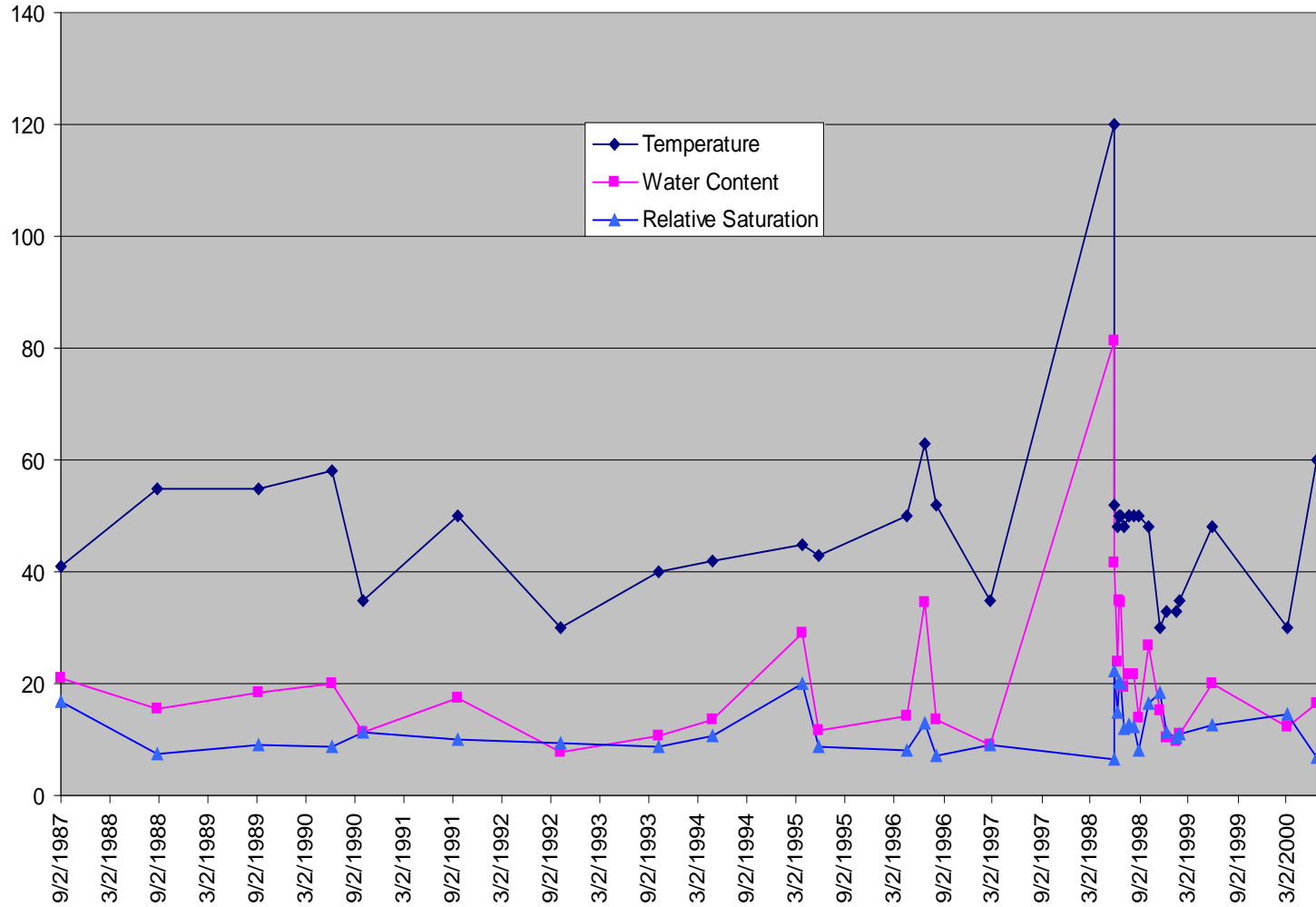
- Moisture in transformers
 - exchange between liquid and solid
 - ppm -vs- relative saturation
 - temperature gradients
 - paper is the moisture reservoir



Case 2



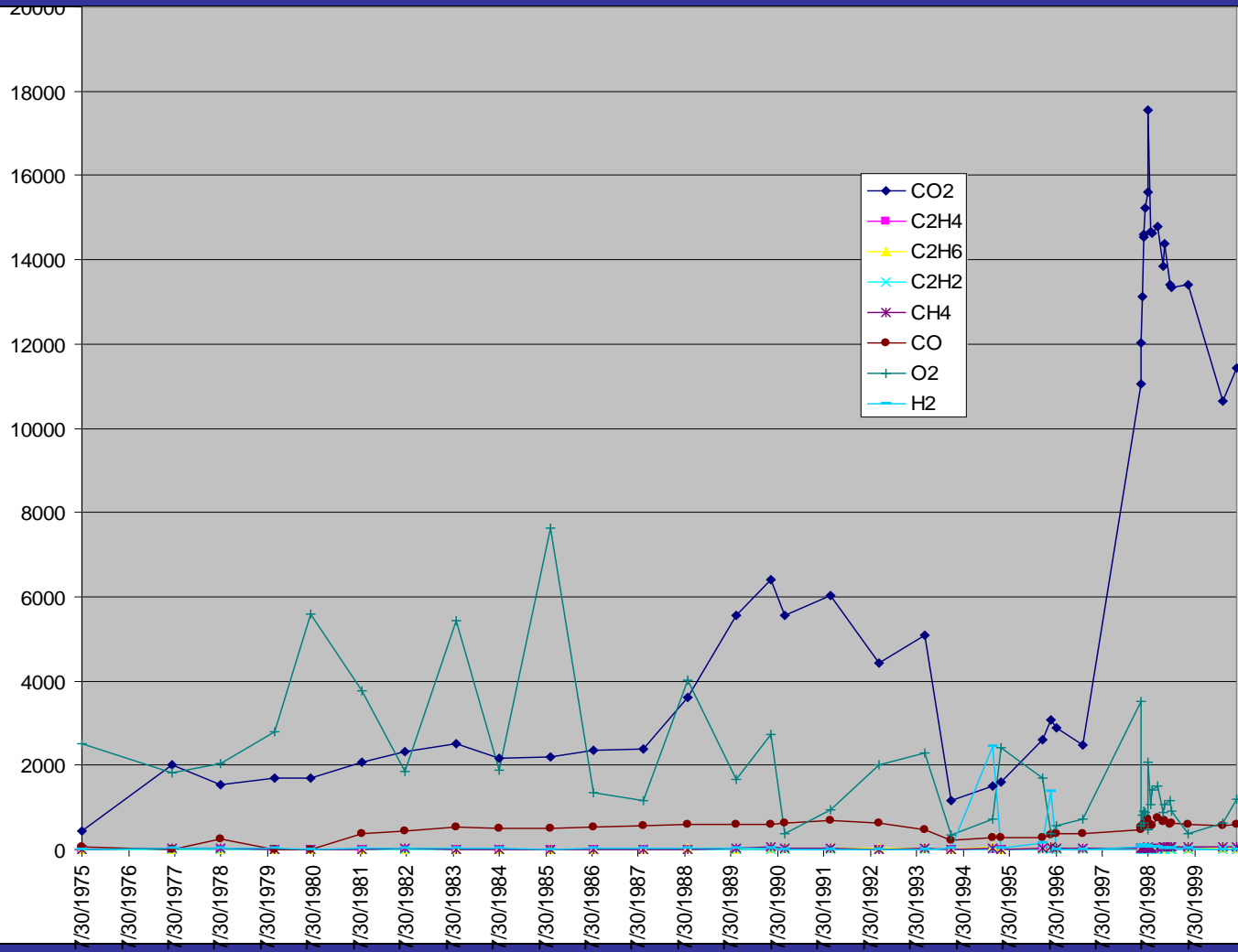
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Case 2



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Overheated Transformer



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	Power Factor, %	
	1993	1998
C_H	.232	.684
C_L	.202	.862
C_{HL}	.642	1.265



Case 3- Preservation System



- Preservation system enhancement
 - TCG decrease
 - CO and H₂
 - largest contributors to TCG
 - most dramatic decrease
 - Hydrocarbon gases
 - slight decrease
-



Case 3



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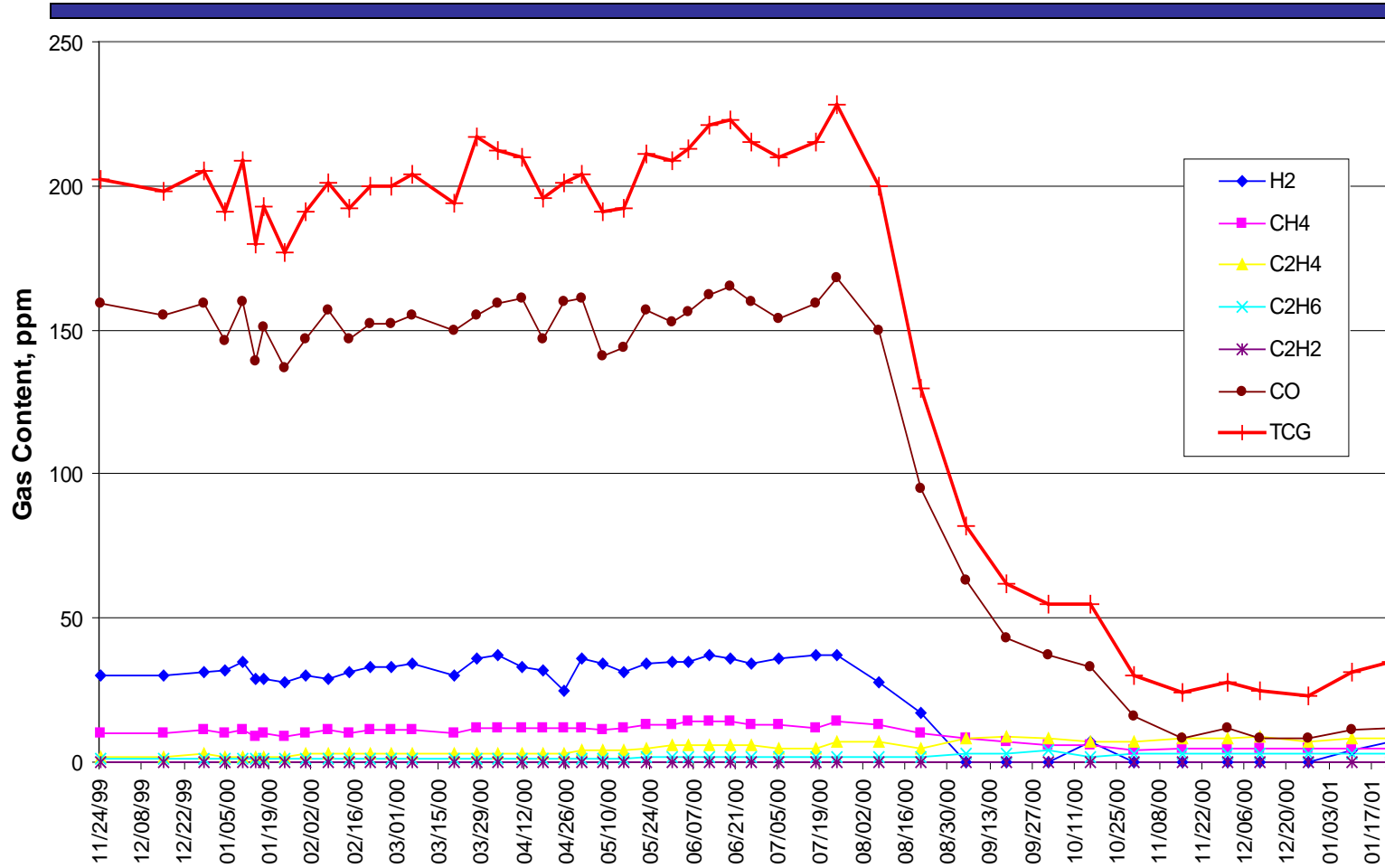
Gas	Ostwald Coefficient
Oxygen	0.138
Nitrogen	0.0745
Carbon Dioxide	0.900
Carbon Monoxide	0.102
Hydrogen	0.0429
Methane	0.337
Ethane	1.99
Ethylene	1.35
Acetylene	0.938



Case 3



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Case 4- Bucholtz Telay



- Single phase, 420 MVA, ASEA, 1972
 - 1996-DGA detected PD
 - 1997-DGA detected overheating of oil-
Three weeks later-PD
 - 7/3/97-bucholtz tripped unit off-line
-



Case 4



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Gas	Main Tank (Oil)		Bucholtz (Gas)
	Conc., ppm 7/3/97 6PM	Conc., ppm 7/3/97 10PM	Conc., ppm 7/3/97 6PM
H ₂	630	260	448410
CH ₄	210	160	9157
C ₂ H ₄	30	30	8524
C ₂ H ₆	10	10	234
C ₂ H ₂	0	0	3342
CO	90	80	2073
CO ₂	230	270	5075
N ₂	--	--	--
O ₂	3000	3000	6300
TCG	970	540	471475



Case 4



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	K @ 50°C	Equiv. Conc. In oil from Bucholtz Gas, ppm
H ₂	0.05	22421
CH ₄	0.40	3663
C ₂ H ₄	1.40	11934
C ₂ H ₆	1.80	430
C ₂ H ₂	0.90	3008
CO	0.12	245
CO ₂	1.00	5075
N ₂	0.09	--
O ₂	0.17	1071



Case 4 - Bucholtz



- Bubble evolution
 - rate of generation exceeded diffusion
 - too far up in tank
 - Investigation
 - Core-to-clamp ground strap disconnected
 - Importance of sampling Bucholtz gas
-



Case 5 - Low Temperature Gassing

Characteristics of Oils - Stray Gassing



Dissolved Gas-in-Oil Content of Aged Samples

	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
Oil A	378	106	63	2	0	215	908
Oil B	122	101	58	10	0	113	1414
Oil C	81	34	20	1	0	65	608
Oil D	35	0	0	0	0	46	489



Case 5 - Low Temperature Gassing

Characteristics of Oils - Stray Gassing



Dissolved Gas-in-Oil Content of Aged Samples After Degassing

	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
Oil A	165	133	99	2	0	116	370
Oil B	0	4	2	0	0	0	42



Case Study 6



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- Manufacturer Federal Pacific
 - kV 230
 - MVA 200
 - Preservation System Gas Blanket
 - Failed Yes
 - Other Three-phase Auto transformer
-



Case Study 6



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GAS	PPM
HYDROGEN	1,500
OXYGEN	2,200
NITROGEN	110,000
METHANE	410
CARBON MONOXIDE	310
ETHANE	31
CARBON DIOXIDE	2,400
ETHYLENE	390
ACETYLENE	880
TCG	3,493



Case 6 - Investigation Findings



- Failure began with shorting and arcing of two leads, one from the preventive auto-transformers and the other from the tap winding to the tap changer terminal board
- Lead vibration and rubbing through of insulation
- Essentially put a short across Phase B of the preventive autotransformer.
- Leads should have been separated and tied down



Case Study 7



- Manufacturer Allis Chalmers
- kV 345
- MVA 500
- Preservation System Gas Blanket
- Failed No



Case Study 7



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GAS	PPM
HYDROGEN	420
OXYGEN	2,800
NITROGEN	89,000
METHANE	4,400
CARBON MONOXIDE	42
ETHANE	950
CARBON DIOXIDE	1,300
ETHYLENE	3,900
ACETYLENE	5
TCG	9,717



Case 7 - Investigation Findings



- Two jack bolts bearing on the brace or on the core yoke were so loose they could be moved by hand
 - Carbon buildup found around these bolts and there were melting marks on the tips of the bolts
-



Case Study 8



- Manufacturer Westinghouse
 - kV 161
 - MVA 60
 - Preservation System Sealed conservator
 - Failed No
 - Other Pump storage generator feeder transformer
-



Case Study 8



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GAS	PPM
HYDROGEN	280
OXYGEN	12,000
NITROGEN	49,000
METHANE	1,500
CARBON MONOXIDE	94
ETHANE	150
CARBON DIOXIDE	960
ETHYLENE	1,200
ACETYLENE	140
TCG	3,364



Case 8 - Investigation Findings



- Visual inspection revealed that most of two turns were burned away and considerable copper beading was distributed around the immediate area of the fault.
- There were two or three of the conductors at the inside of the turn still intact.

