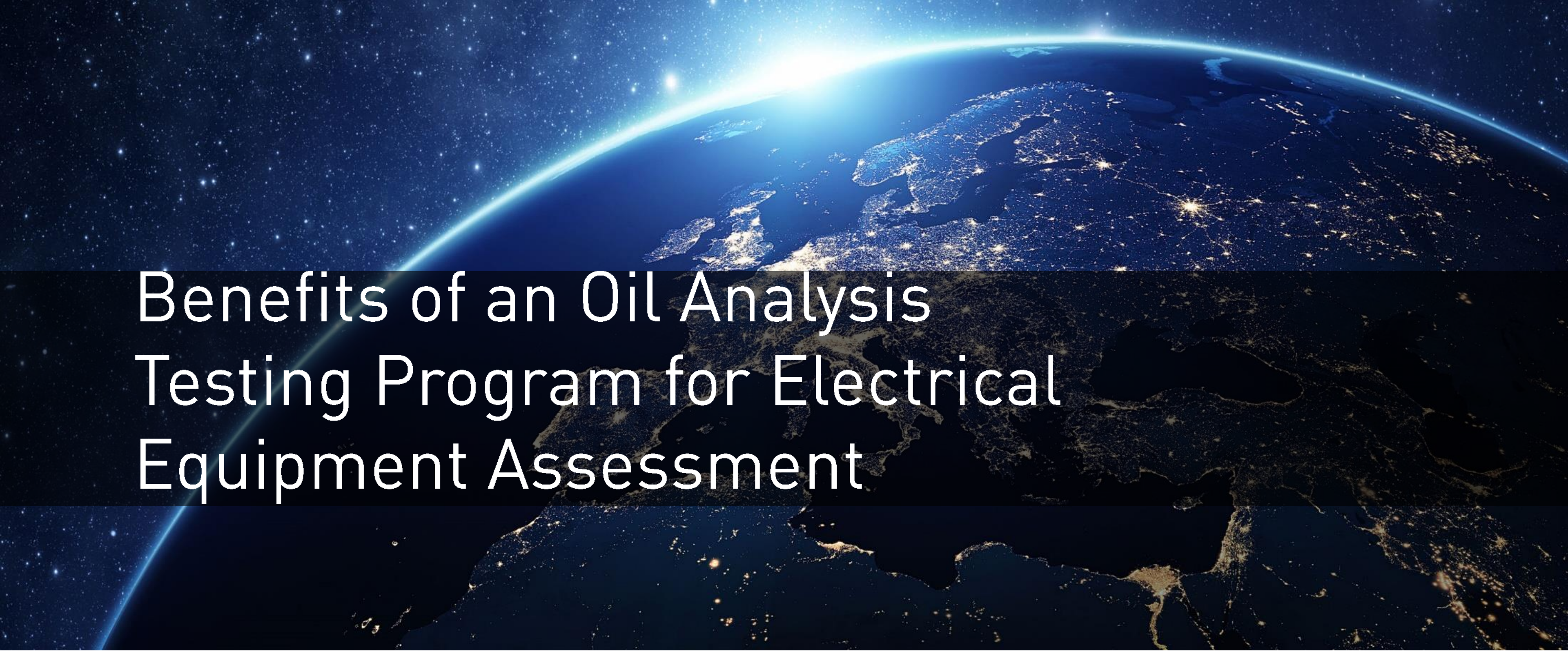


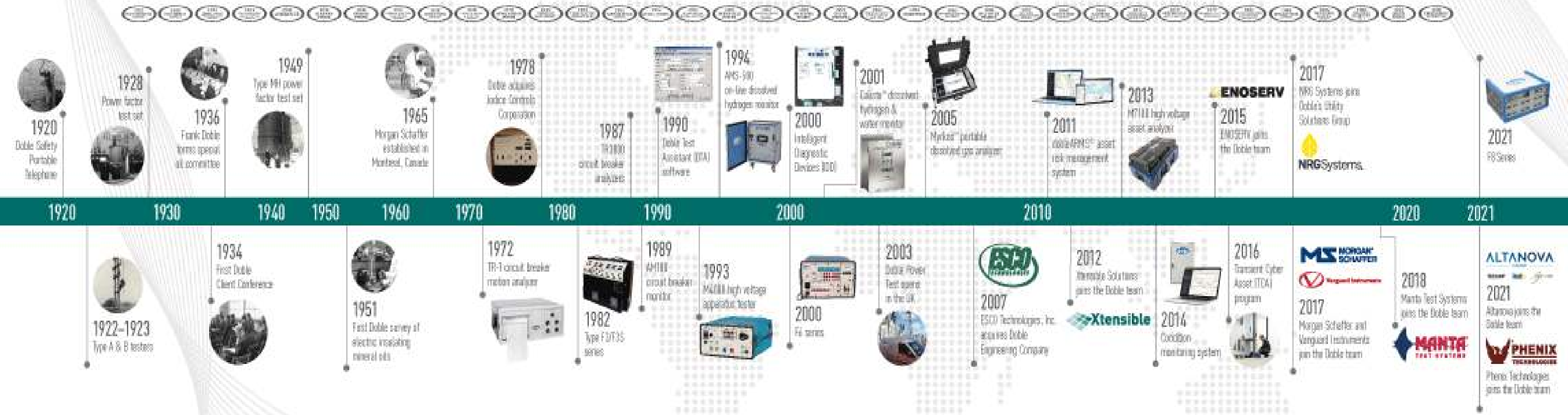
Benefits of an Oil Analysis Testing Program for Electrical Equipment Assessment

Engineering expertise and advanced diagnostics to ensure that all people globally have ***reliable***, ***safe*** & ***secure*** energy in a sustainable world

BUILT ON OVER A CENTURY OF INNOVATION AND EXPERTISE.

FOR THE NEXT CENTURY.

100 YEARS OF SERVICE TO THE ELECTRIC UTILITY INDUSTRY



DOBLE TODAY

110 COUNTRIES

12 GLOBAL OFFICE LOCATIONS

800+ EMPLOYEES

5,550+ CUSTOMERS GLOBALLY

Part of ESCO Technologies' Utility Solutions Group

OUR BRANDS

isa · MORGAN SCHAFFER · PHENIX TECHNOLOGIES · TECHIMP · Vanguard Instruments

ENSURING RELIABILITY IN THE FACE OF RAPID CHANGE

- Clean Energy Transition
- Growing demand for electricity
- Distributed energy & renewables
- Evolving cybersecurity & regulatory requirements
- Keeping up with the IoT
- Artificial intelligence & emerging technologies

With an eye toward the future, Doble will help utilities navigate change – just as we have for the past 100 years.

OPTIMIZE PERFORMANCE WITH DOBLE

PRODUCTS & SOLUTIONS

- Condition monitoring
- Enterprise Asset Management
- Protection testing
- Off-line testing & assessment
- Consulting & testing services
- In-service testing and assessment
- Security & compliance
- Oil standards

Transformers | Bushings | Circuit Breakers | Rotating Machines | Protective Relays | Cables

Agenda

This webinar will provide an overview of the following topics:

- Dissolved Gases in Oil
- Why assessing the wetness of the insulation system is important
- Tests to assess the condition of the paper and pressboard insulation
- Case studies
- Q&A

Why Measure Gases in Oil

- Most important diagnostic in the industry
- Excellent indicator of developing faults
- Detect of wide range of problems
- Sensitive in the early stages of development of faults
- Provides information on materials involved in fault
- Provides indication of severity and need for remedial action
- But it can be complex - not easily simplified for analysis in all cases

DGA-Common Faults and Issues Detected

Partial Discharge

Paper Pyrolysis

Low Temp Thermal

High Temp Thermal

Floating Potential

Arcing

Leak Check Gas

Stray Gassing

Passivator Outgassing

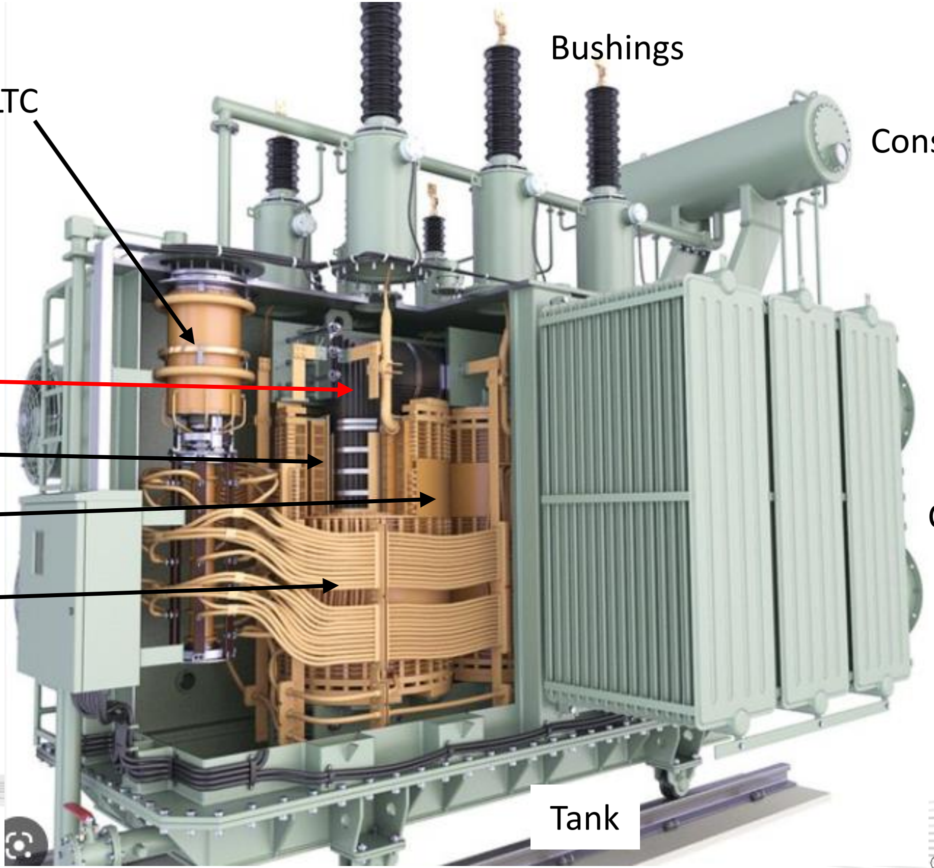
Compromised Bladder and/or gaskets

Leak From Tap Changer

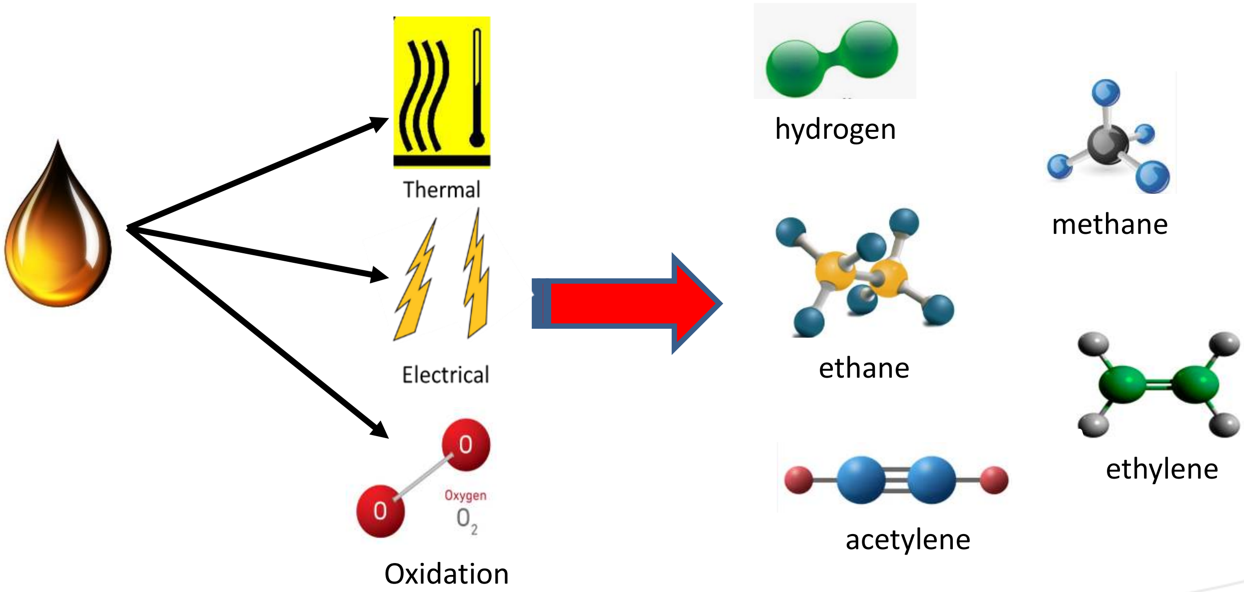
Contamination

Transformer – Materials Can Cause Gas Formation

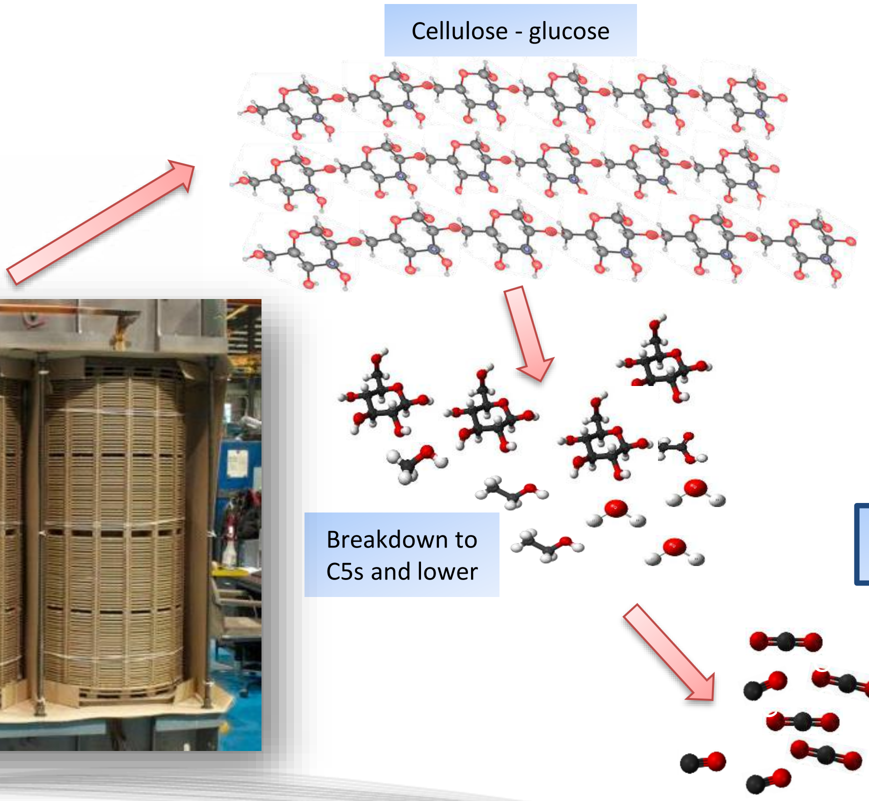
- Steel
- Paint
- Gaskets
- Varnishes
- Glues
- Oils
- Fiberglass
- Paper
- Phenolics
- Copper
- Aluminum
- Brass
- Stainless
- Solders

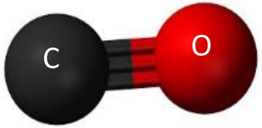


How Gases are Formed – Insulating Liquids

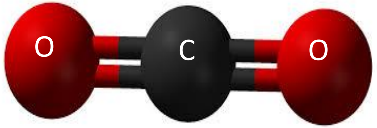


Gases Generated from Paper Decomposition





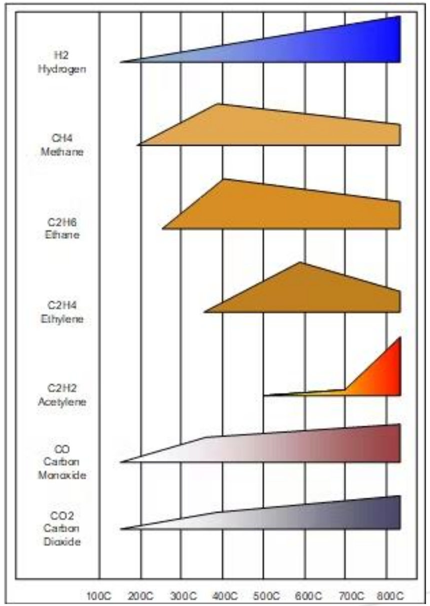
Carbon Monoxide



Carbon Dioxide

Gas Formation: Mineral Oil

Temperature °C	Gases Formed	Symbol	Energy Required kJ/mole
~120	Hydrogen	H_2	338
↓	Methane	CH_4	338
	Ethane	C_2H_6	607
	Ethylene	C_2H_4	720
>700	Acetylene	C_2H_2	960



https://www.tdworld.com/test-and-measurement/article/20972772/building-a-transformer-health-index-part-2

Temperature Profiles

Gas	Overheating Oil
methane and/or ethane, sometimes hydrogen	Low temperature, <300°C
ethylene (mainly)	300 to 700°C
ethylene with any acetylene	Local hotspot >700°C

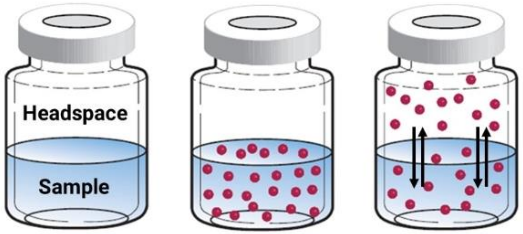
Combustible and Non-Combustible Gases

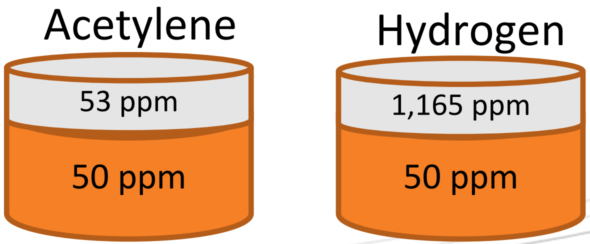
Combustible Gas	Symbol	TCG
Hydrogen	H_2	**TCG** = Total Combustible Gas ppm (parts per million) **$H_2 + CH_4 + CO + C_2H_6 + C_2H_4 + C_2H_2$**
Methane	CH_4	
Carbon Monoxide	CO	
Ethane	C_2H_6	
Ethylene	C_2H_4	
Acetylene	C_2H_2	

Non-Combustible Gas	Symbol
Carbon Dioxide	CO_2
Oxygen	O_2
Nitrogen	N_2

Partition Coefficients (Basis for Method C)

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





Interpreting DGA Data

- Norms - What is a normal amount
- Total combustible gas - Guidelines
- Key gases - Identification of type of problem
- Ratios -Identification of type of problem (Rogers, IEC 60599, others)
- Trends - What’s new, gassing rates
- Fingerprints - Typical gassing behavior for certain transformer
- Solid insulation – is paper or other cellulosic materials involved
- Stray gassing – Is the issue sensitive of the oil to overheating
- Duval Triangles and Pentagons
- NEIs (Normalized Energy Index)

Interpreting Dissolved Gas Data

- Nameplate information including age
- Historical data trends
- Has the Total Combustible Gas risen suddenly?
- Is the unit heavily loaded or overloaded?
- Has the oil been processed
- Did a bushing or the transformer fail at some point?
- If the unit has been repaired, was the oil filtered or degassed?

Dissolved Gas Limits Various Sources

Criterion	H_2	CO	Methane	Ethane	Ethylene	Acetylene	CO2	TCG
DOBLE	100	250	100	60	100	5 (1)*	10,000 –core** 20,000-shell**	610
IEEE C57.104+ $O_2/N_2 \leq 0.2$ $O_2/N_2 > 0.2$ (2019)	200 90	1100 600	100-200 30-60	70-250 30-40	40-175 80-125	2-4 7	7000-14000 7000-8000	
IEC 60599 (ranges)	50-150	400-600	30-130	20-90	60-280	2-20 (No OLTC) 60-280 (Communicating OLTC)	3800-14,000	

Values based on statistical norms or consensus values

*Would consider 1 ppm or more of acetylene as abnormal for further evaluation

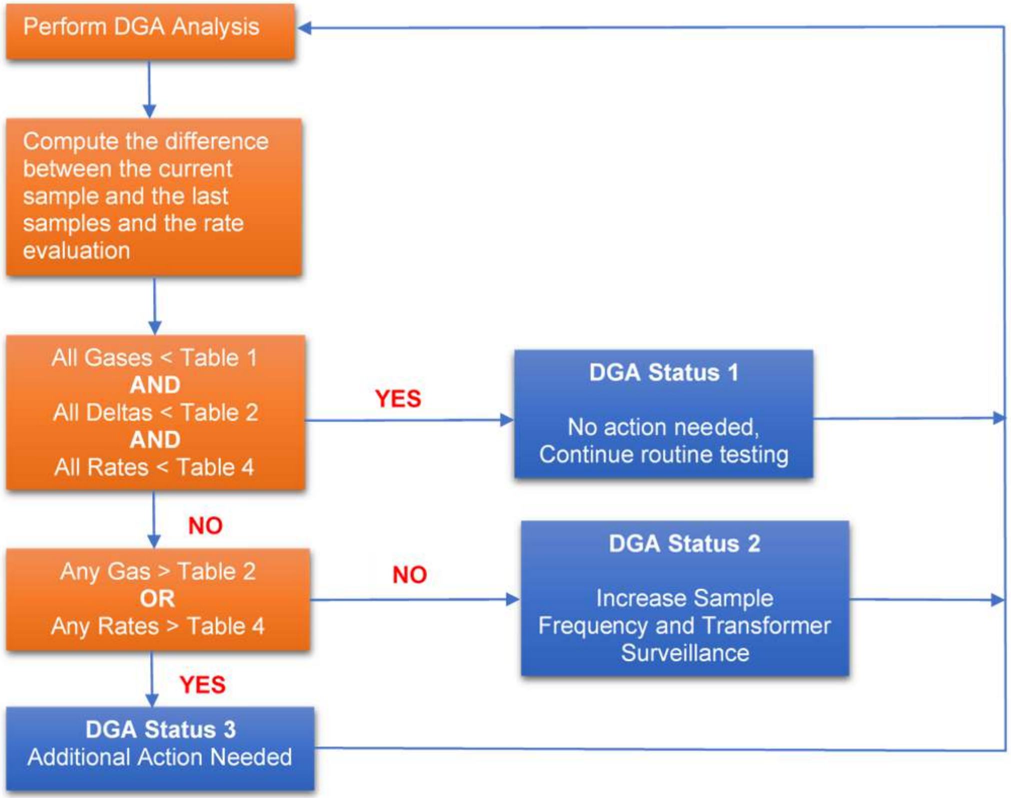
**Empirically based guidelines

+IEEE 2019 95th Percentile-ranges cover transformers of different ages

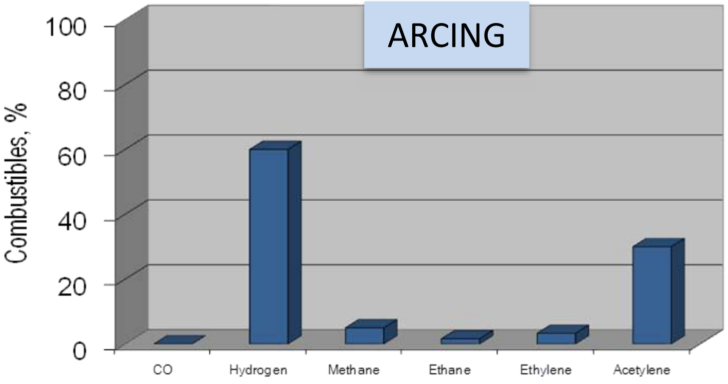
IEEE C57.104 2019

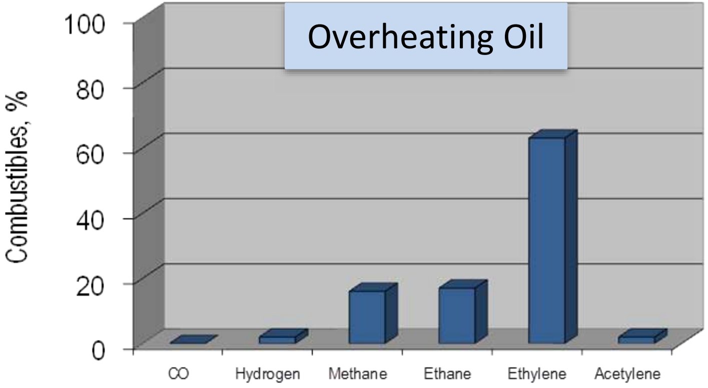
Status	Definition
DGA Status 1	Screening DGA results are acceptable. Continue routine operation
DGA Status 2	Incipient or modest recent gas production or moderately elevated gas level. Resample to confirm and monitor gas evolution.
DGA Status 3	High gas levels or continuing significant gas production. Mitigative actions or other response should be considered (ie continuous monitoring)

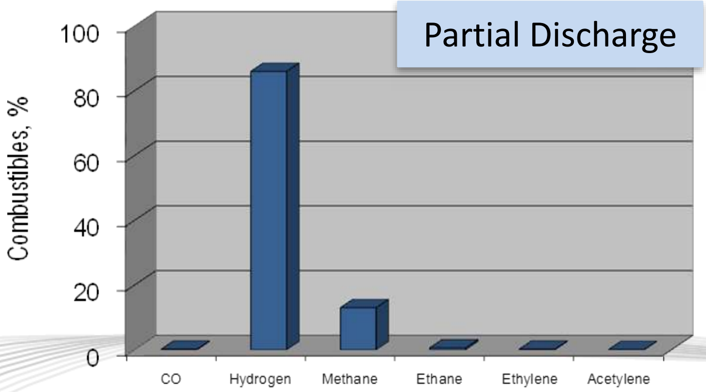
IEEE C57.104 2019 Flowchart

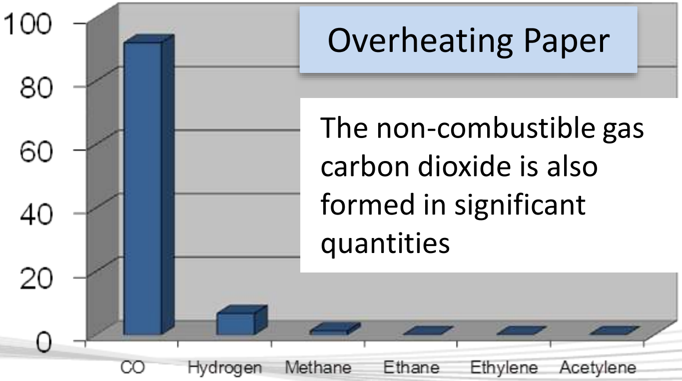


Key Gases


ARCING
Combustibles, %
100
80
60
40
20
0
CO
Hydrogen
Methane
Ethane
Ethylene
Acetylene


Overheating Oil
Combustibles, %
100
80
60
40
20
0
CO
Hydrogen
Methane
Ethane
Ethylene
Acetylene

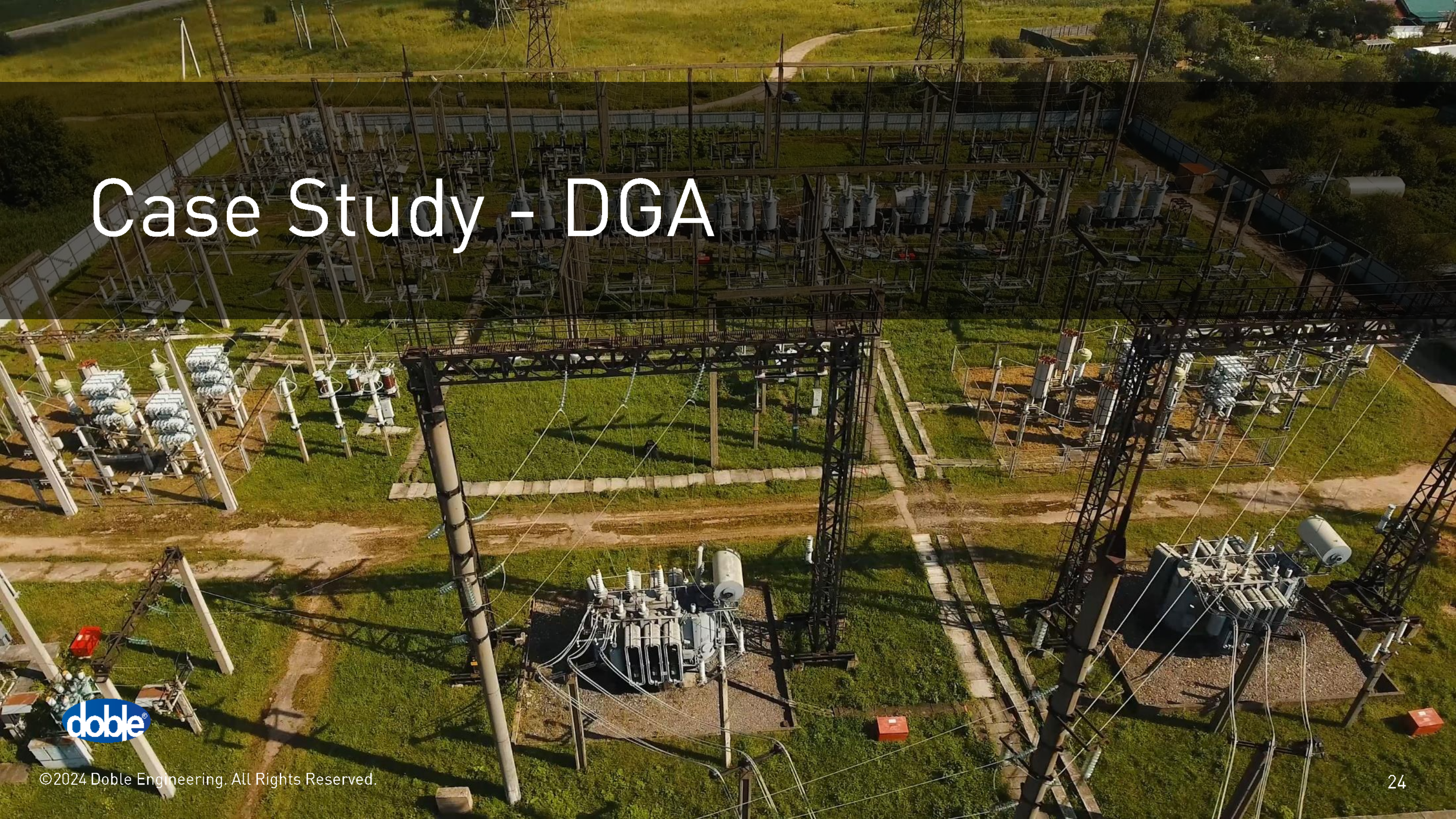

Partial Discharge
Combustibles, %
100
80
60
40
20
0
CO
Hydrogen
Methane
Ethane
Ethylene
Acetylene


Overheating Paper
The non-combustible gas carbon dioxide is also formed in significant quantities
100
80
60
40
20
0
CO
Hydrogen
Methane
Ethane
Ethylene
Acetylene

Carbon Oxide Gases and Ratios

- Cellulose Insulation
- Shell form > CO_2 than Core form
- Accidental CO_2 from air
- CO_2/CO ratio approaching 1 = high temperature faults
- High CO_2 with low CO-lack of cooling/general overheating
- CO_2/CO ratio trend declining indication of paper overheating

Case Study - DGA



Problems After Factory Rewind

- 1992 General Electric 115kV transmission transformer
- Rewind performed after flashover event caused damage to low voltage C phase winding
- Unit passed all post-repair electrical and oil tests
- Transformer was energized and ~50% loaded for one year

Problems After Factory Rewind

Dissolved gases-in-oil	After Fault – Before Repair, ppm	After Repair, ppm	1-Year After Repair, ppm
Hydrogen	151	0	26
Methane	23	0	74
Carbon Monoxide	394	3.0	84
Ethane	5.8	0	30
Carbon Dioxide	4,740	53	466
Ethylene	6.9	0	99
Acetylene	7.3	0	Trace

Rise in Ethylene Values

- Transformer put on bi-monthly sampling schedule, ethylene continues to increase

Sample Date	Hydrogen	Oxygen	Nitrogen	Methane	Carbon Monoxide	Ethane	Carbon Dioxide	Ethylene	Acetylene
08/14/2017	0	3700	12300	0	3.0	0	53	0	0
07/10/2018	20	7,070	73,900	64	64	28	385	95	0
08/14/2018	26	6,010	78,600	74	84	30	466	99	Trace
08/30/2018	24	6,810	81,400	75	81	32	513	103	Trace
09/14/2018	24	5,770	75,800	77	83	34	540	107	Trace
09/28/2018	25	9,980	95,600	82	92	36	568	114	0
10/16/2018	25	5,120	77,400	82	92	35	543	111	Trace

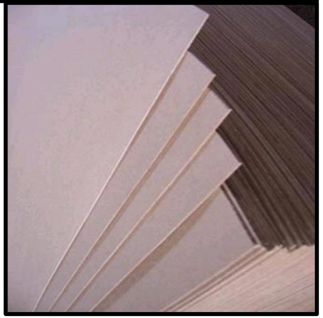
Problems After Factory Rewind

- Bent lamination tips made contact with the tank wall
  - Pressboard spacers were missing
- Rise in ethylene due to unintentional ground/circulating currents

Why assessing the wetness of the insulation system is important

Where Is Water Located

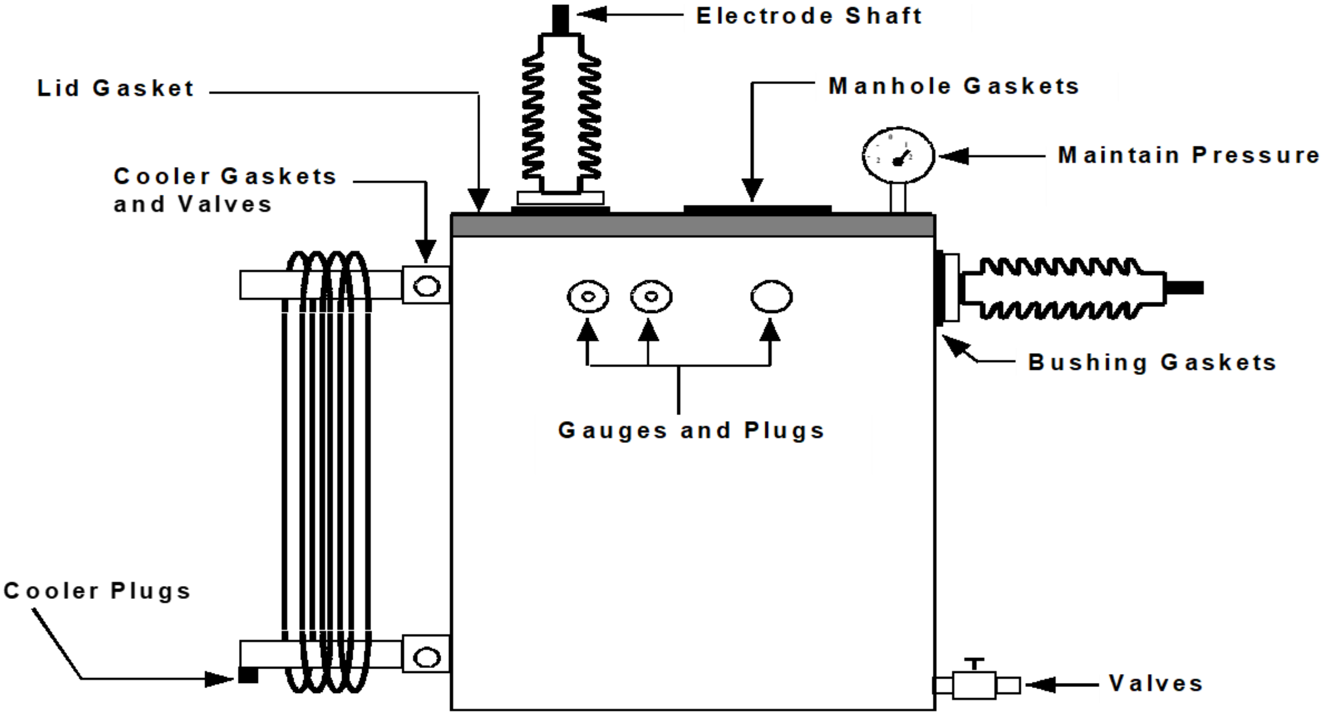
- Most of the water is located in the solid cellulosic insulation
  - Wood
  - Paper
  - Pressboard
- The amount in the oil is often <1% of the total



Entry Points for Water in Transformers

- Residual after processing:
  - Manufacturing
  - Installation
  - Maintenance
- Leaks
  - Through weak points of transformer
- Transformer Preservation System
  - Ineffective dryers - breathing conservators
  - Ruptured bladder/diaphragm - sealed conservators
- Byproduct of Cellulosic Degradation

Water Ingress Points



What is the Importance of Water

- Four Main Reasons
  - Dielectric strength is a function of water content
    - Dielectric Strength decreases with increasing water content
    - Creep strength of insulation decreases with increasing water content
  - Rate of paper aging is directly proportional to water content
  - Risk of bubble formation during overloads function of water in paper content
  - Risk of condensation during cool down increases with increasing water content

Solubility

- Solubility (100% Saturation) of water in oil is defined as the amount of dissolved water an oil can hold at a specific temperature
- Solubility changes significantly with temperature
- As oil temperature increases, its ability to hold water also increases
- For example, solubility of water in oil at 10°C is 36 ppm, whereas at 90°C the solubility is 592 ppm
- As oils age and accumulate large amounts of acids and other polar compounds solubility increases

Solubility of Water in Insulating Liquids, ppm

Temp, °C	Mineral Oil	Silicone	Askarel	Natural Esters	Synthetic Esters
0	22	88	43	631	1207
10	36	125	63	787	1452
20	55	174	91	966	1726
30	83	237	127	1171	2028
40	122	316	175	1402	2358
50	174	414	236	1661	2717
60	243	533	313	1948	3104
70	333	678	408	2263	3518
80	448	849	523	2607	3960
90	594	1051	662	2981	4428
100	775	1286	827	3385	4921

For Example

- An oil sample was taken from a transformer at:
  - top oil temperature 85°C
  - 30 ppm water in oil
- To determine the relative saturation
  - measured water (30 ppm)
  - divided by the solubility at 85°C (517 ppm)

$$Relative\ Saturation\ (RS) = \left(\frac{30}{517}\right) \times\ 100\% = 5.8\%$$

Low %RS and High %RS Oil

Water Content
30 ppm

Temperature, 50°C

Low RS

Visual Appearance is Clear

Water Content
30 ppm

Temperature, 0°C

High RS

Visual Appearance is Cloudy

Dielectric Strength

Substantially lowered when

- Water content of paper/pressboard significantly reduced as the water content increases to 2 to 4%
- The dielectric breakdown voltage of the dielectric liquid is reduced about in proportion to the relative saturation of water
  - The breakdown voltage is reduced by about 50% when the RS is 50%

Condensation

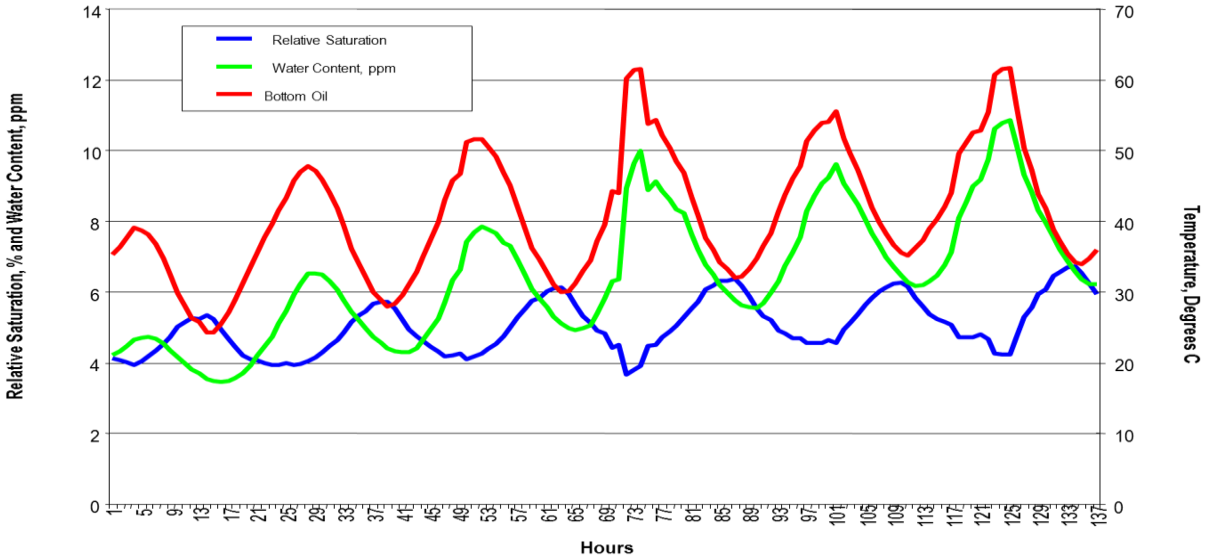
- Cool down period of thermal transient
  - Water migrates from paper→oil with increasing operating temperature (due to load & ambient temp)
  - At higher temperature, moisture migration is quicker and the solubility of water in oil is high
  - During cool down, water remains mostly in the oil for a long timeas diffusion in paper is slow … solubility also decreases
  - Excessive water…High RS…low dielectric breakdown voltage
  - Condensation possible

Excessive Water in Oil - Cool Down Period of Thermal Transient

- Most susceptible in transformers that
  - are wetter (> 1.5% in paper)
  - temperature cycle
  - temperature cycle quickly and to great extremes
  - operate at lower temperatures

Continuous Measurement in a Transformer

- Water content is not static but forever changing based on a number of conditions…
- Dictates the need for a continuous measurement



The dielectric strength of a insulating liquid correlates well to the relative saturation as opposed to the concentration level in ppm

Tests to assess the condition of the paper and pressboard insulation

Insulating Materials

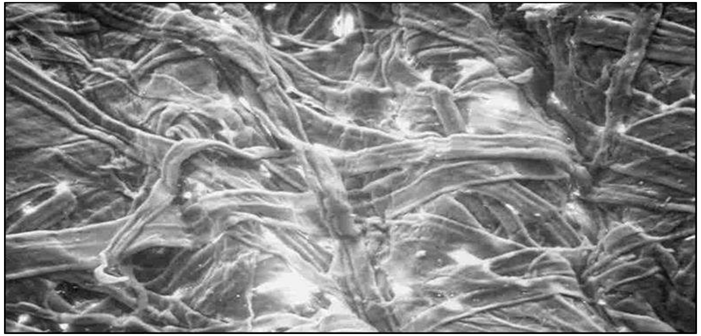
- Principal Insulating Components
  - Paper
  - Mineral Oil
- Aging Factors
  - Heat
  - Water
  - Oxygen

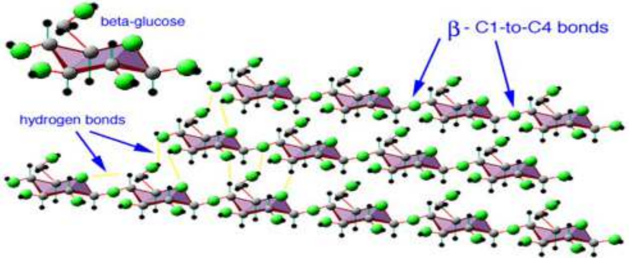
- Control Factors to Reduce Aging
- Influence Paper and Oil differently
- Paper more critical component
- Oil easily replaced

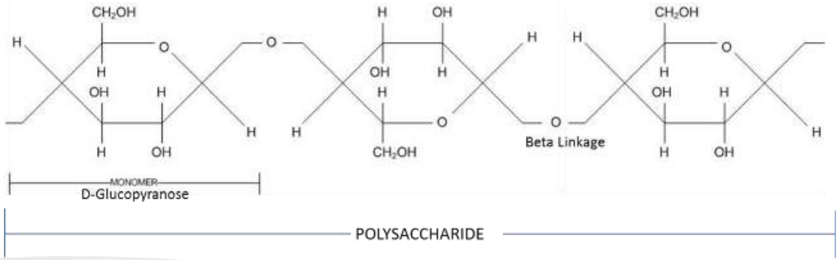
Cellulose

- Manufacturer's design life at nameplate rating about 20 years, many transformers >30 years old
- Cellulose
  - Availability and price
  - Retains insulating properties when deteriorated
  - Formability
- Typical Life 40 + years
  - If sealed units operated at or below nameplate ratings
- Causes of aging of Cellulose by priority
  - High temperature
  - Water
  - Oxygen
  - Copper catalyst, contaminants

Cellulose – Chemical Structure



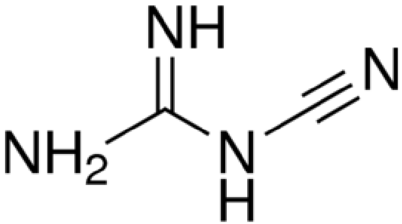




- Average chain length: 1000 to 1300 units
- Aging leads to shorter cellulose chains

Aging Characteristics-Paper

- Thermally Unstable
  - Every 6-8^{o}C rise, half the life
  - Arrhenius-type kinetics
    - $K_o=Ae^{B/T}$
  - Thermally upgraded (TU) more stable than Kraft paper



Temperature °C	Estimated Life to DP 200, TU Kraft (Years)	Estimated Life to DP 200, Kraft (Years)
40	110,838	22,918
60	6,229	1,291
80	485	101
90	151	31
100	50	10
110	17	3.6
140	1	0.2
180	0.04	0.01

Aging Characteristics: Paper

Water

- Significant effect
- Rate of deterioration α water content
    - 0.5% to 1.0%: Half life
- Thermally Upgraded Kraft more stable than Kraft

Oxygen

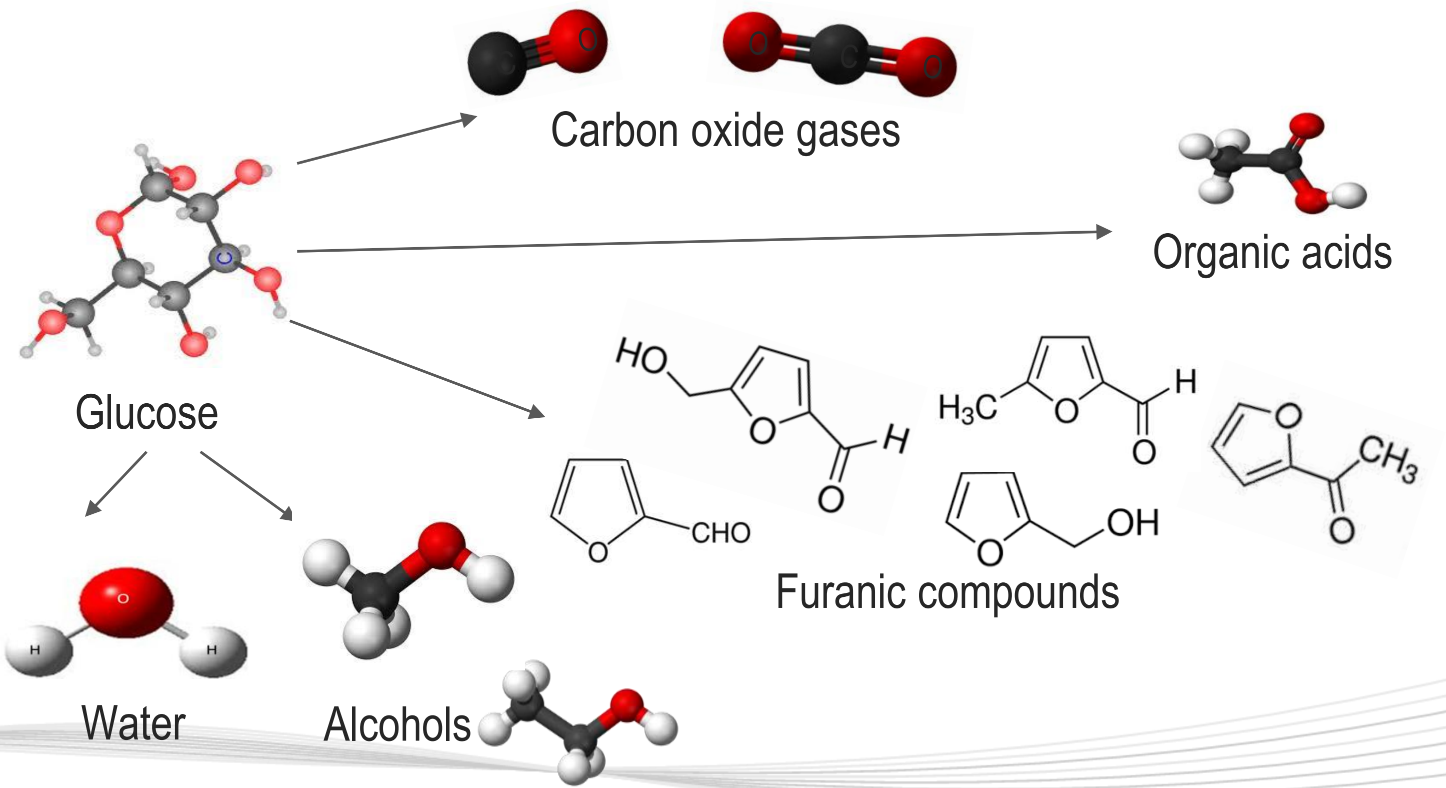
- Oxidatively stable
- 2.5:1 High O_2:Low O_2
- Preservation system
- Thermally Upgraded Kraft more stable than Kraft

Aging Of Materials

- Ambient temperature -influences operating temperature
- Transformer physical location (ventilation)
- Loading, pump operation, cooling design
- Inherent stability of materials
- Position/location within unit
- Presence of incipient-fault condition
- Factors not uniform over time

Cellulose Degradation Indirect Tests

Usually performed through an oil sample



Partition Coefficients

- Partitioning between paper where furanic compounds are formed and oil
- Temperature
- Wet paper reduces partitioning to the oil
- Oil Quality (as oil degrades, has more polar compounds and increase partitioning of furanic compounds into the oil)
- Generation rate may be based on quantity of paper in transformer and thermal upgrading

Effects of Electrical Discharge

- Furanic compounds not detected in high quantities when cellulosic materials subjected to sustained electrical discharges
  - Cellulosic insulation severely damaged locally
  - Carbon monoxide produced in proportion to amount of paper involved
- Theory: Electrical discharges produce very high temperatures (>1200°C)
  - Furanic compounds are generated
  - But immediately degraded due to temperature

Precautions

- Kraft paper in open conservator usually provides the best trending - higher amounts of furanic compounds formed
- Hard to tell if high concentrations are from small amount of insulation at high temp. or larger mass at lower temp.
- Processing transformer oil will alter concentrations - sample before and after (a few months) processing to re-establish baseline

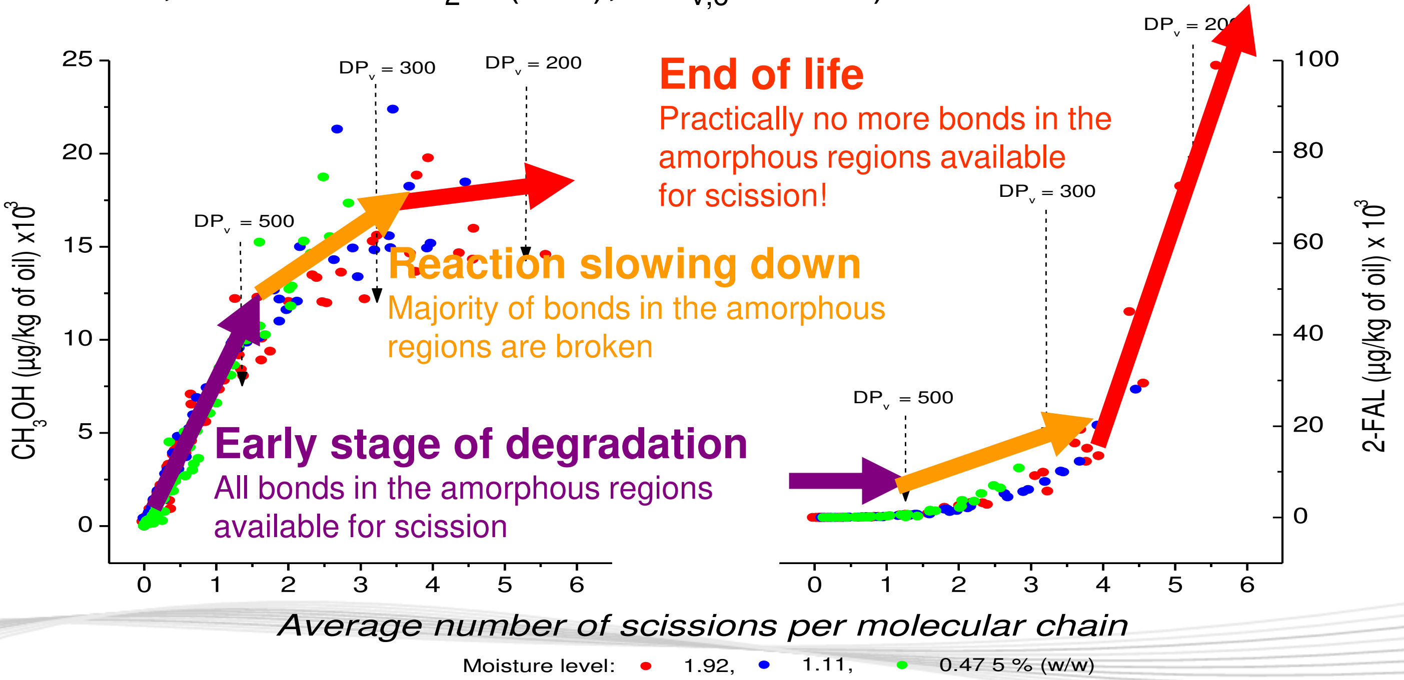
Alcohol Detection

- Methanol and Ethanol
- Drawbacks about 2-furfural
  - TU-paper…Very low concentrations detected
  - Standard Kraft paper:
    - Amount of 2-furural influenced by the water-in-paper content

Laboratory Aging

More realistic model marker

Standard Kraft paper specimens aged at different moisture-temperature conditions (60 to 120ºC – 0,47 to 1.92% H_2O (w/w), $DP_{v,o}$ = 1168)



Courtesy of IREQ, Varennes, Canada

Comparison of Methanol and Furanic Compounds

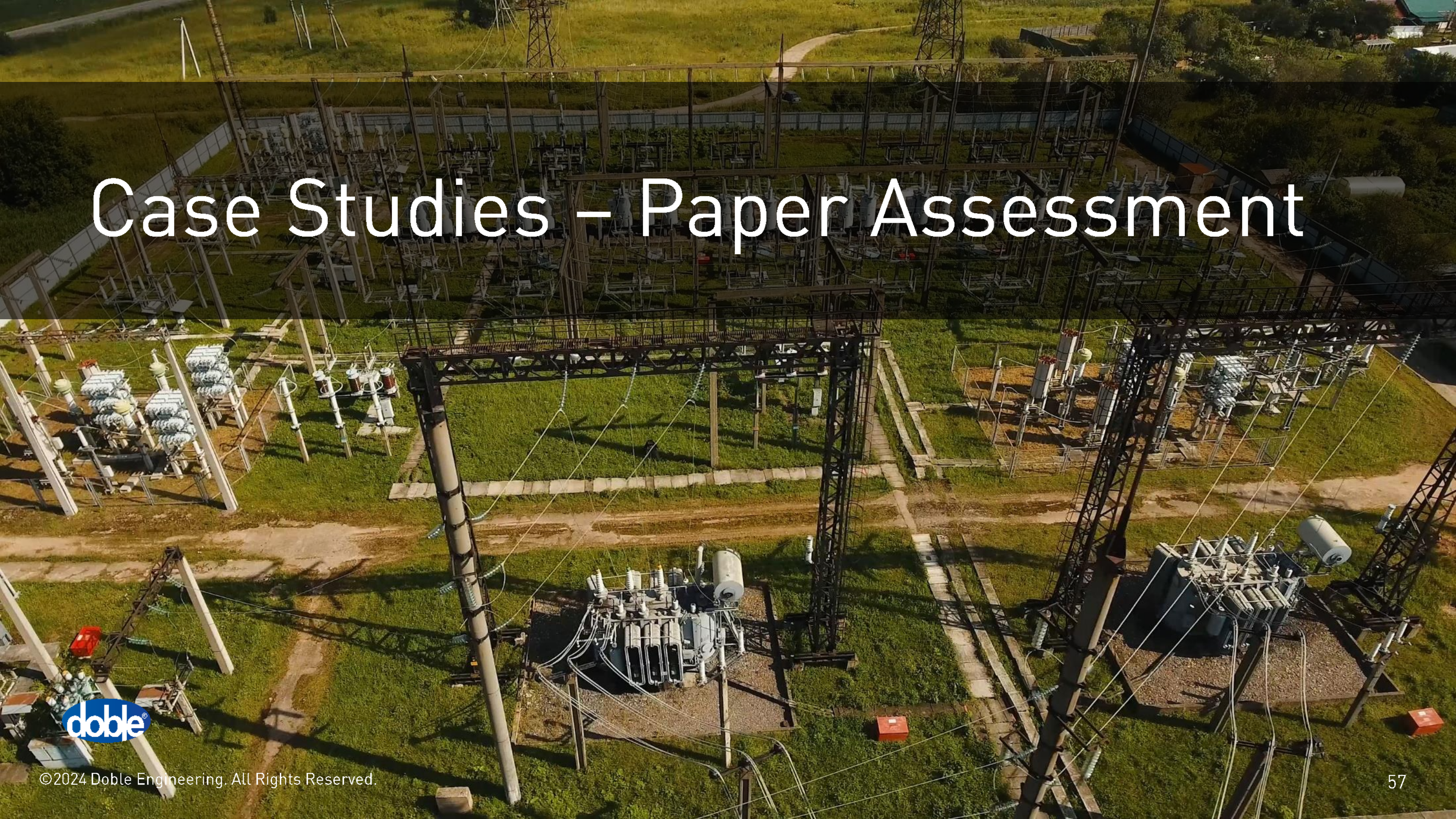
- Based on laboratory experiments
  - Methanol might be more reliable than 2-furfural
    - Detected for regular Kraft and TU Kraft papers
    - Not influenced by the amount of moisture in paper
    - Sensitive at the early stage of cellulose degradation
    - Correction to 20°C is required

- For testing electric apparatus
  - More information to compare apparatus and pinpoint problems (Asset Management)
  - More information for refurbishment decision
  - Will suffer the fate of furanic compounds when subjected to oil processing
  - Must take sample in syringe in order not to lose volatile alcohols

Reduction of Aging

- Keep sealed and dry - check seals and gaskets, nitrogen bottle, nitrogen pressure
- Conversion of open conservators in some cases
- Operate at cooler temperature
- Valves in correct position, cleaning coolers, adequate ventilation
- Locate blocked coolers by infrared thermography

Case Studies – Paper Assessment



Very High Furanic Compounds and Carbon Oxides

Transformer Nameplate	Details
Manufacturer	Unknown
Apparatus Type	Grounding transformer, core form
MVA Rating	11.5
kV Rating	33
Preservation System	Nitrogen blanketed
Oil volume	Unknown
Paper Type	Kraft
Loading	Heavy in cyclic periods
Year Manufactured	Around 1944, about 50 years of service
Condition	Taken out of service before failure, was seen steaming in a rain storm, temperature gauged pegged at over 200°C

Very High Furanic Compounds and Carbon Oxides

Dissolved gases-in-oil	ppm
Hydrogen	1,980
Oxygen	unknown
Nitrogen	unknown
Methane	318
Carbon Monoxide	2,990
Ethane	98
Carbon Dioxide	58,300
Ethylene	42
Acetylene	0

Furanic Compound	ug/L
2-furfural	35,124

- Grounding transformer
- Connected to sub-transmission feeder with line capacitors
- High side fuses blown causing overloading during certain switching functions due to imbalances in current of each of the three phases
- Probably occurring several days a week for at least 2 years

Elevated Ethanol

Transformer Nameplate	Details
Manufacturer	Magnetek
Apparatus Type	Transformer, core form
MVA Rating	22.4
kV Rating	138
Preservation System	Nitrogen blanketed
Oil volume	4050 gallons
Paper Type	Thermally upgraded
Loading	unknown
Year Manufactured	1986
Condition	Did not fail - Tested because oil quality degraded very quickly in 2 years

Elevated Ethanol

Dissolved gases-in-oil	ppm
Hydrogen	139
Oxygen	3,270
Nitrogen	36,800
Methane	123
Carbon Monoxide	825
Ethane	104
Carbon Dioxide	8,060
Ethylene	30
Acetylene	0

Furanic Compound	ug/L
5-HMF	< LD
FOL	< LD
2-FAL	255
AF	29
MF	< LD

Alcohols	ppb
Methanol	200
Ethanol	1,313

- Ethanol suggests high temperature overheating of cellulose > 300°C, other tests do not


Thank you!