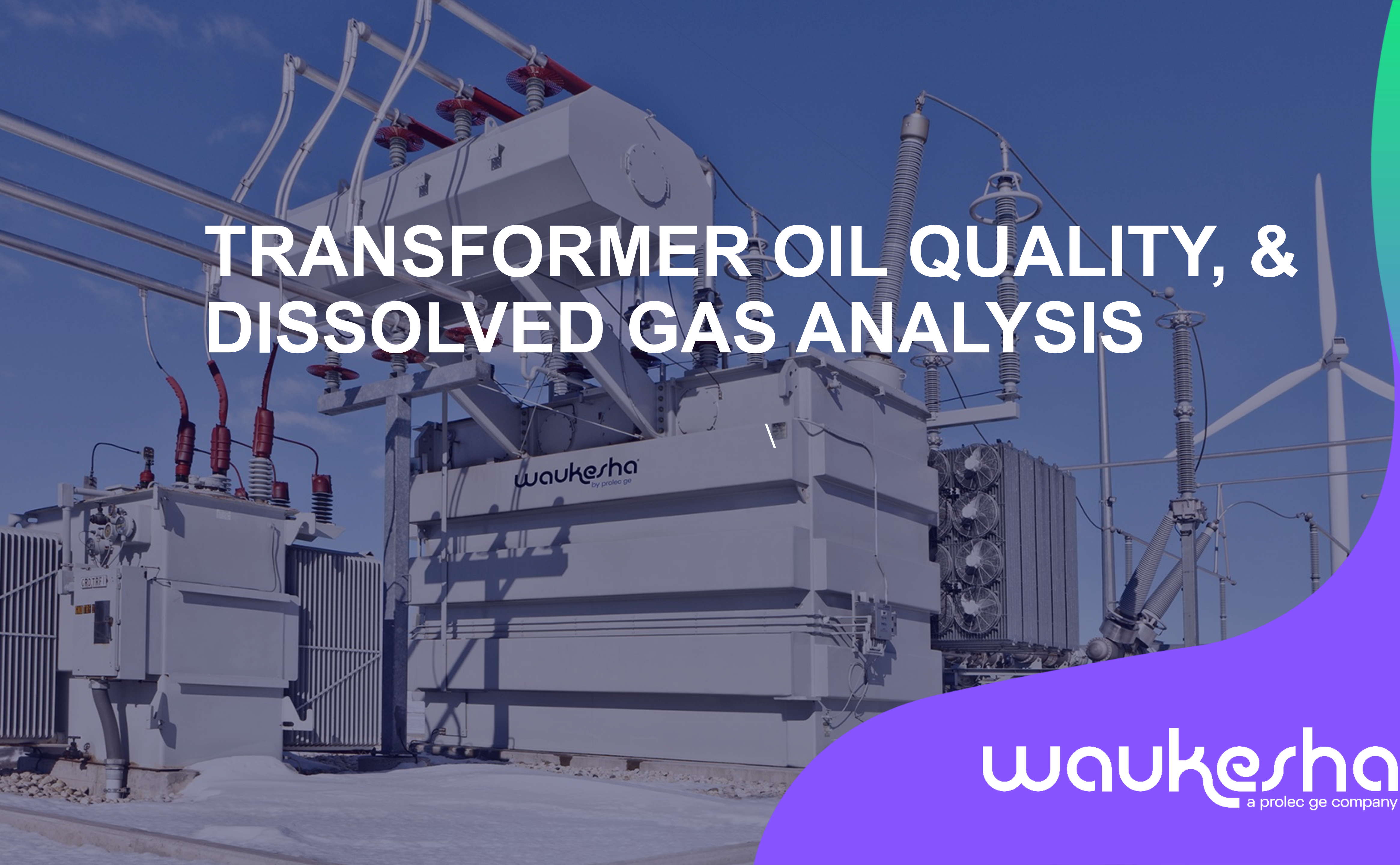

TRANSFORMER OIL QUALITY, & DISSOLVED GAS ANALYSIS

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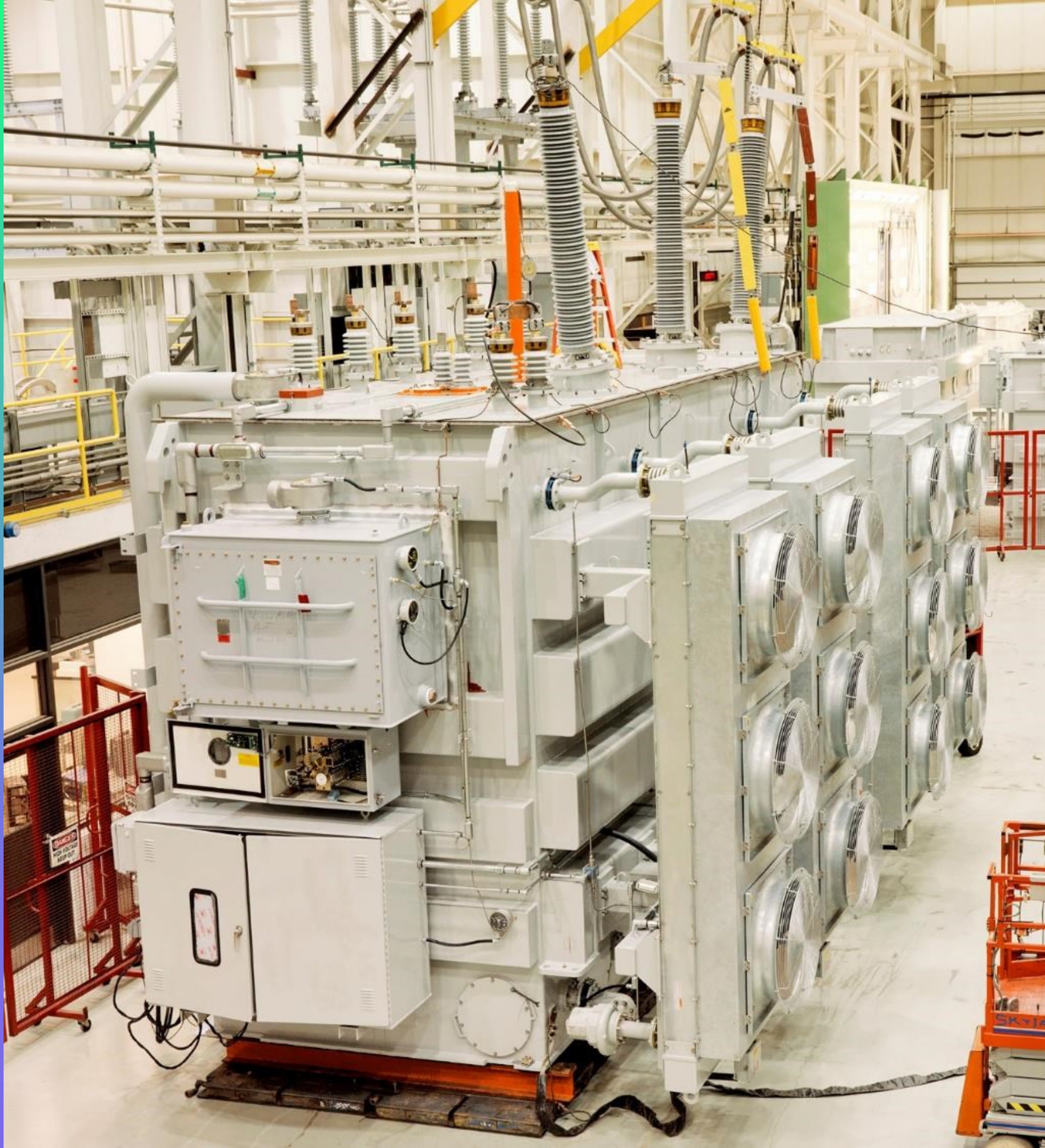
Agenda

1. Insulating Fluids
2. Reconditioning
3. Dissolved Gas Analysis
4. Post Fault Analysis

Insulating Fluids



Purpose of Transformer Insulating Fluids

- To provide dielectric insulation between sources of voltage and ground
- To provide cooling to the transformer windings
- Contaminants in the oil reduce its ability to perform these two essential functions

Transformer Insulating Fluids

- Various fluids are used in transformers and electrical components
- They all have a tendency to absorb moisture and air when exposed to atmosphere
- Inadvertent mixing of one oil type with another can cause severe foaming under vacuum

Transformer Insulating Fluids (cont.)

Some of the Major Transformer Insulating Fluids

- Mineral Oil
- R-Temp (higher viscosity)
- Silicone-based oil
- Natural ester fluids

Insulating Fluid Treatment & Reconditioning

Glossary of Common Terminology

Degasify

- Removal of air and other gases from transformer oil and transformer by applying high vacuum

Dehydrate

- Removal of water from the transformer oil and transformer by high vacuum

Reconditioning

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Reconditioning of oil is required to improve moisture content or dielectric breakdown of the oil.

- Accomplished with vacuum purification equipment
- Process can be completed on-line or off-line
- Reducing moisture concentration of oil by recirculation of oil within transformer tank has limited improvement of moisture content of the cellulose insulation

Transformer Drying Theory

Degasifying

- Oil absorbs air up to its saturation point (about 12% by volume) by exposure to air

Benefits of Degasifying

Removal of oxygen reduces oxidation deterioration of oil

Degasified oil better impregnates cellulose insulation

Remaining bubbles trapped under surfaces as oil fill progresses are absorbed into the oil

Removal of any combustible gases generated during transformer use

Improves insulating quality of the oil (air is a better conductor than oil)

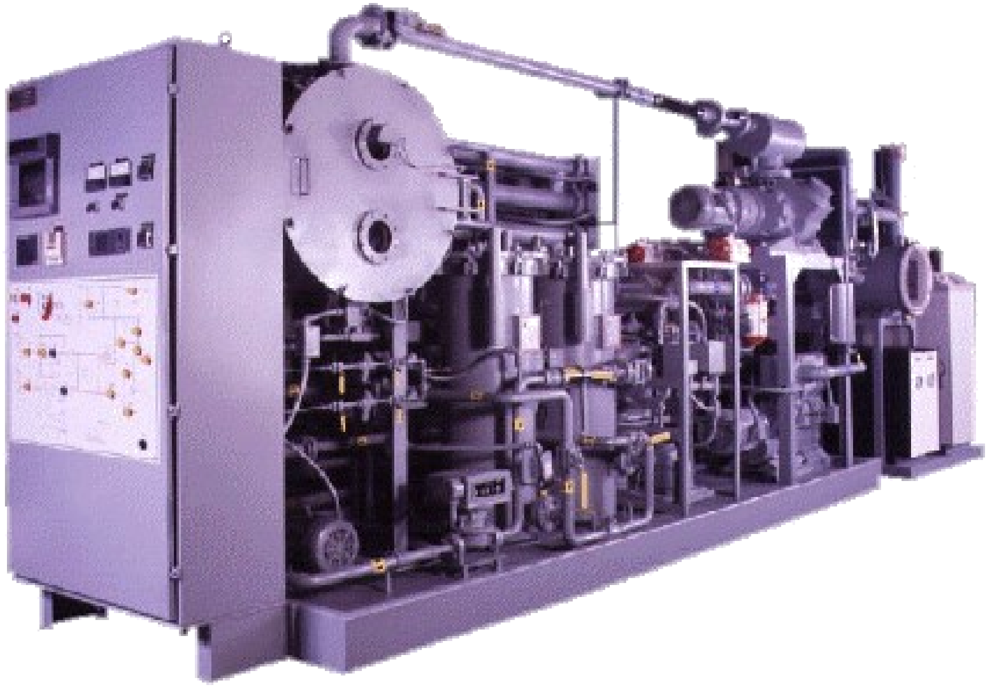
Transformer Drying Theory

Dehydration: ***Importance of Removing Water from the Insulation***

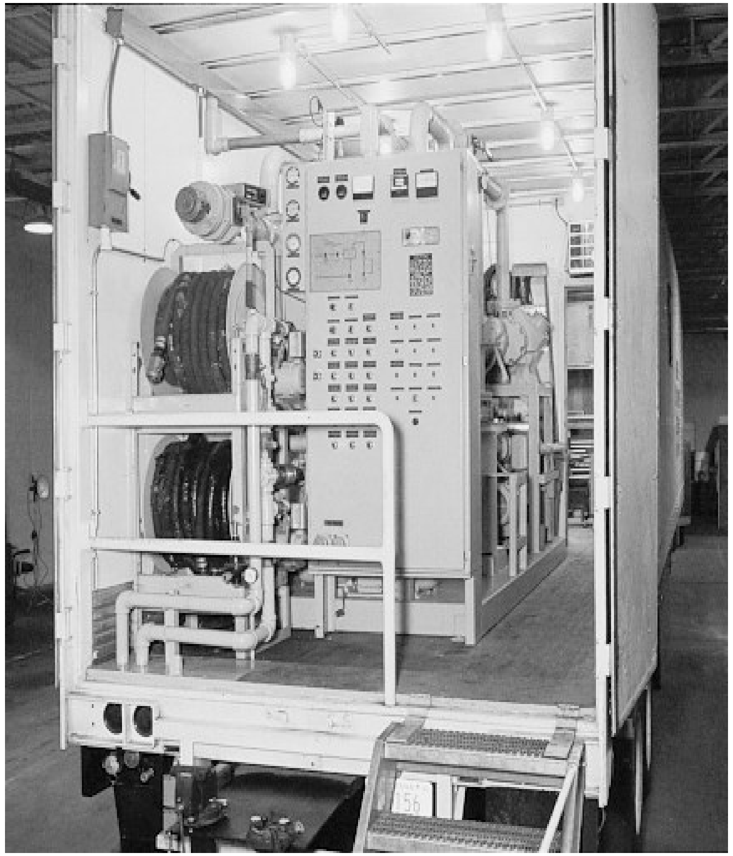
- If water is removed from the oil only:
  - Large percentage of the total water in the system will still remain
  - After the transformer is returned to service, water in the insulation will migrate to the drier oil until equilibrium is met and the transformer will test wet
- Rate of aging of the cellulose materials is directly proportional to the water content, e.g. if water content is doubled from 1 to 2 percent, the life is halved
- Low water content of solid insulation permits greater extremes in temperature cycling without impairing the dielectric integrity of the system

Purpose of Vacuum Purification Equipment

- Remove water and gas vapors from solid insulation within the transformer
- Reduce the moisture content of the insulating fluid
- Remove solid particulate from the fluid
- Reduce soluble gasses from the insulating fluid



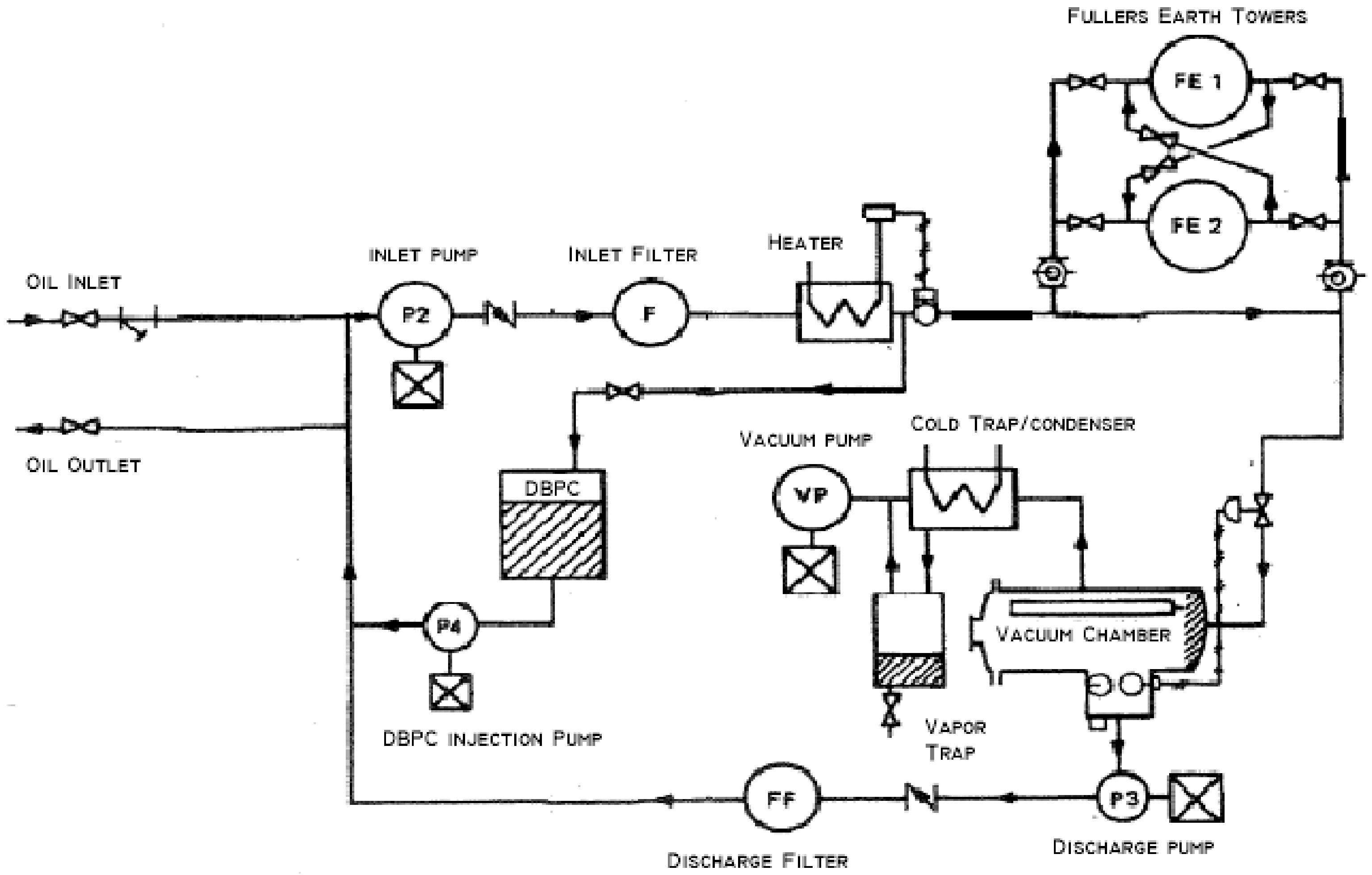
Equipment Requirements



Equipment Must Be Capable of Doing the Following:

- Reduce total gas content to less than 0.2%
- Lower dissolved water content to less than 10 PPM
- Remove 96% of all particles greater than the nominal pore size of discharge filter
- Operate at temperatures ranging from 50°F to 180°F
- Achieve flow rate of 1200 GPH
- Achieve blanking pressure of less than 50 microns

Vacuum Oil Purification Equipment



Vacuum Purification System Flow Diagram
Figure 1

Degasification

Degasification of oil is required when elevated levels of dissolved gas concentrations are observed…

- TDCG concentrations approaches IEEE category 4 (4630 PPM)
- TDGC approaches solubility limits for sealed systems
- Process can be done on line or off line
- Degasification by recirculation may not remove all gases from insulation.

Oil Processing Equipment: Vacuum Dehydration

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Water is removed from the oil by:

- Spreading into a thin film and exposing it to vacuum
- Water in the oil will boil at low pressure for the same reasons discussed earlier
- Water vapor is then pumped away by the vacuum pumps
- The higher the vacuum, the better the degree of water removal

Oil Processing Equipment: Vacuum Degasification

Gases are removed from the oil by:

- Spreading into a thin film and exposing it to vacuum
- Gas in the oil will flow out to the low pressure much like a soda with the lid removed
- Gases are then pumped away by the vacuum pumps
- The closer to absolute the vacuum, the better the degree of gas removal

Oil Processing Equipment: Cold Trap

Dry Ice and Acetone/ Liquid Nitrogen

- Can be mounted on top of transformer
- Uses either liquid nitrogen or a slurry or dry ice and acetone to cool the thimble
- Water freezes to the thimble and therefore can be collected for measurement
- Protects vacuum pumps from water contamination and makes them more efficient since water is removed from the air stream before going through the pump

Oil Processing Equipment – Cascade Cold Trap

Cascade Cold Trap

- Usually mounted in the trailer, in a separate trailer or sits on the ground.
- Uses electric power and refrigeration to chill freeze plates.
- Water freezes to the plates providing the same benefits as the previous trap but without need for liquid N2, dry ice or acetone.
- Heated defrosting allows rapid ice thawing and speedy measurement.

Oil Processing Equipment: Mechanical Filtration

Solid particles are removed from the oil by:

- Passing the oil through treated paper elements that have a pore size that allows the oil to pass through but stops solid particles larger than the pore size
- These elements are typically disposable and are replaced when they begin to plug with trapped particles

Oil Processing Equipment – Fullers Earth Treatment

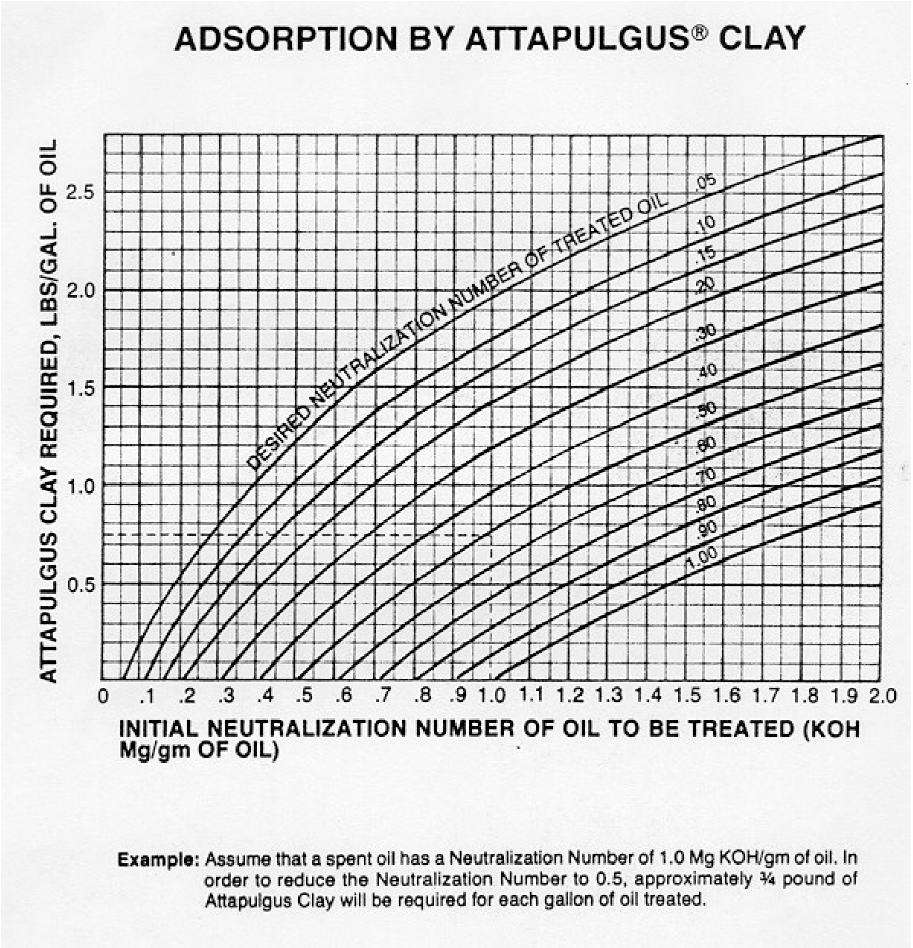
Sludge is removed from the oil by:

- Flowing hot oil that has already been dehydrated through a bed of bulk fullers earth.
- Sludge particles are too small to be filtered with paper filters.
- Fullers earth removes these and other polar contaminants by adsorption which is the attraction of polar contaminants and release of non-polar compounds

Oil Processing Equipment – Fullers Earth Treatment

Acid is removed from the oil by:

- Flowing hot oil that has already been dehydrated through a bed of bulk fullers earth.
- The amount of fullers earth that is required to alter the Neutralization number from a given value back to within specification can be estimated from this chart.



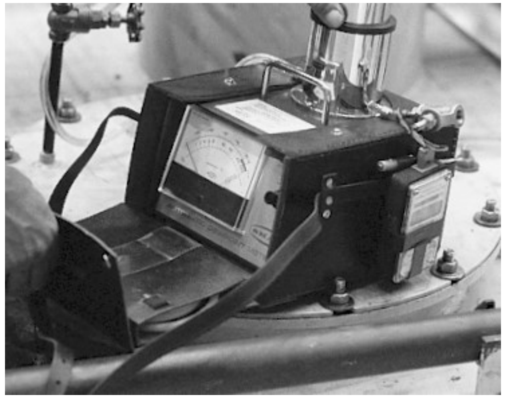
Oil Processing Theory – Fullers Earth Treatment

Oil color is corrected by:

- Flowing hot oil that has already been dehydrated through a bed of bulk fullers earth.
- Color, Acid Number and IFT are related and are all corrected with fullers earth.

Color Classification	Acid (Neut.) No. mg/KOH/g	Interfacial Tension Dynes/CM
GOOD	0.03 to 0.10	30-45
PROP A	0.05 to 0.10	27-29
MARGINAL	0.11 to 0.15	24-27
BAD	0.16 to 0.40	18-24
VERY BAD	0.41 to 0.55	14-18
EXTREMELY BAD	0.66 to 1.50	9-14
CLASS 7 OILS	1.50 and higher	6-9

Equipment Requirements



Beyond the vacuum purification system, other required materials include:

- Dew pointer
- Oil test equipment
- Vacuum gauges
- Vacuum and oil hoses
- Oil storage tanks
- Miscellaneous pipe fittings

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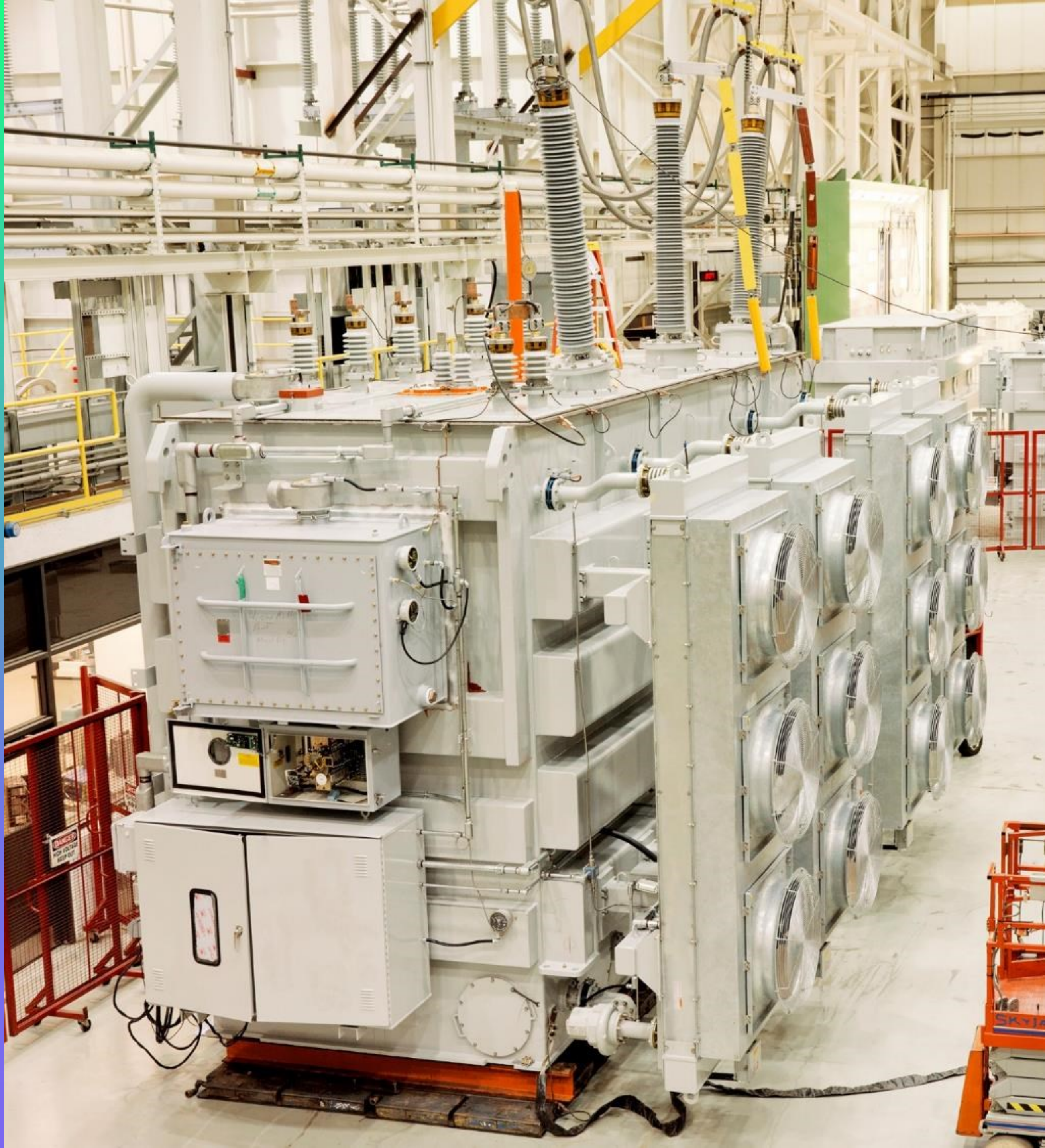
Oil Quality



Classification of Service Aged Oils

Test	Standard	Unit	Voltage	Group 1	Group 2	Group 3	Group 4
Dielectric Breakdown	ASTM-D1816 w/ 1mm gap	min, kV	< 69 kV	23	<23	-	-
			69 - 288 kV	28	<28	-	-
			≥ 345 kV	30	<30	-	-
Neutralization Number	ASTM-D974	max, mg KOH/g	< 69 kV	0.2	-	>0.2	>0.5
			69 - 288 kV	0.15	-	>0.15	>0.5
			≥ 345 kV	0.1	-	>0.10	>0.5
Interfacial Tension	ASTM-D971	min, Dynes/cm	< 69 kV	25	-	<25	<18
			69 - 288 kV	30	-	<30	<18
			≥ 345 kV	32	-	<32	<18
Moisture Content	ASTM-D1533	max, PPM @60°C Avg. Oil Temp.	< 69 kV	35	>35	-	-
			69 - 288 kV	20	>20	-	-
			≥ 345 kV	12	>12	-	-
Power Factor	ASTM-D921	max, %	< 69 kV	0.5	-	>0.5	>1.0
			69 - 288 kV	0.5	-	>0.5	>1.0
			≥ 345 kV	0.5	-	>0.5	>1.0

Group I. Oils that are in satisfactory condition for continued use
Group II. Oils that required only reconditioning for further service
Group III. Oil in poor condition. Such oil should be reclaimed or disposed of depending upon economic considerations
Group IV. Oils in such poor condition that it is technically advisable to dispose of them

Classification of Service Aged Oils

Temperature (degrees C)	Water in Oil	Water in Paper
20°	1	3,000 times what is in the oil
40°	1	1,000 times what is in the oil
60°	1	300 times what is in the oil

The table above shows the tremendous attraction that paper insulation has for water. The ppm of water in oil shown in the DGA is only a small part of the water in the transformer. It is important that, when an oil sample is taken, you record the oil temperature from the top oil temperature gage.

Furan Testing to Determine Aging Process

Table IV – Furan, DP and % of Remaining life

2FAL (ppb)	DP Value	Estimated percentage of remaining life	Suggested Interpretation
58	800	100	Normal Ageing Rate
130	700	90	
292	600	79	
654	500	66	Accelerated Ageing Rate
1464	400	50	
1720	380	46	
2021	360	42	
2374	340	38	Excessive Ageing Danger Zone
2789	320	33	
3277	300	29	
3851	280	24	High Risk of Failure
4524	260	19	
5315	240	13	End of expected life of paper Insulation and Transformer
6245	220	7	
7337	200	0	

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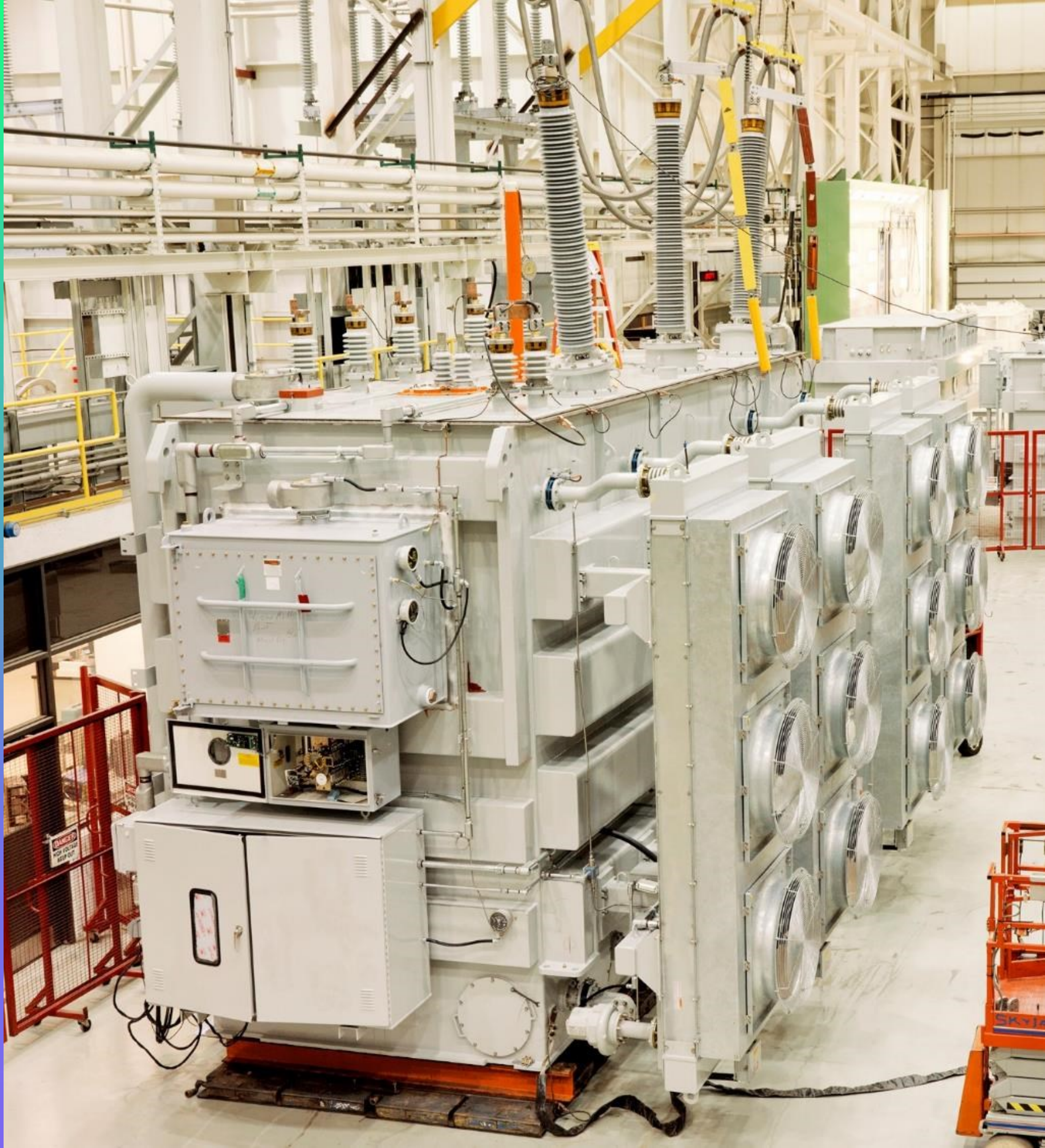
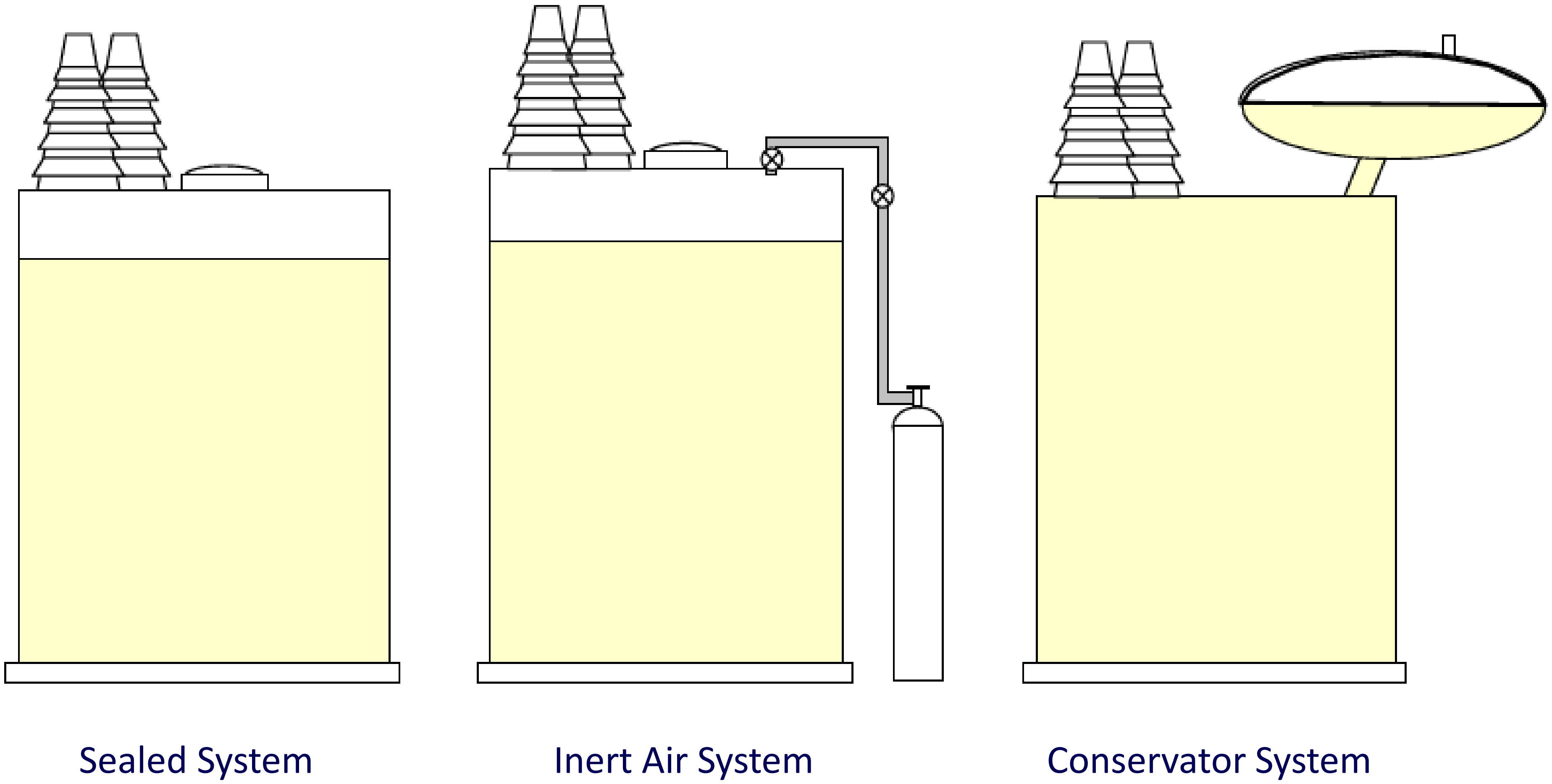
Oil Analysis



Dissolved Gas Analysis – Why Important??

- Transport, installation and intrusive maintenance can damage or compromise a transformer’s electrical insulation system
- In service, transformers are subject to thermal, mechanical and electrical stresses that can cause deterioration and break down solid and liquid insulation
- The degradation of the electrical insulation system generates gases that are characteristics of the material and temperatures involved
- The analysis of types of gas, their concentrations, and the rates of generation can be used to determine the condition of the transformer and plans for maintenance, reconditioning, or replacement.

Transformer Oil Preservation Systems



Dissolved Gas Analysis – Collection Point

Gas Blanket or Gas Accumulation Relay

- The gas concentration and ratios are different in the gas space than in the oil based at different temperatures and relative solubility in the oil.
- Gas space concentrations must be converted to oil concentrations before diagnostic techniques can be applied.
- Gases generated in the oil take time to partition into the gas space and achieve equilibrium, which can delay detection of a problem.

Bulk Oil Collection (Sample Valve)

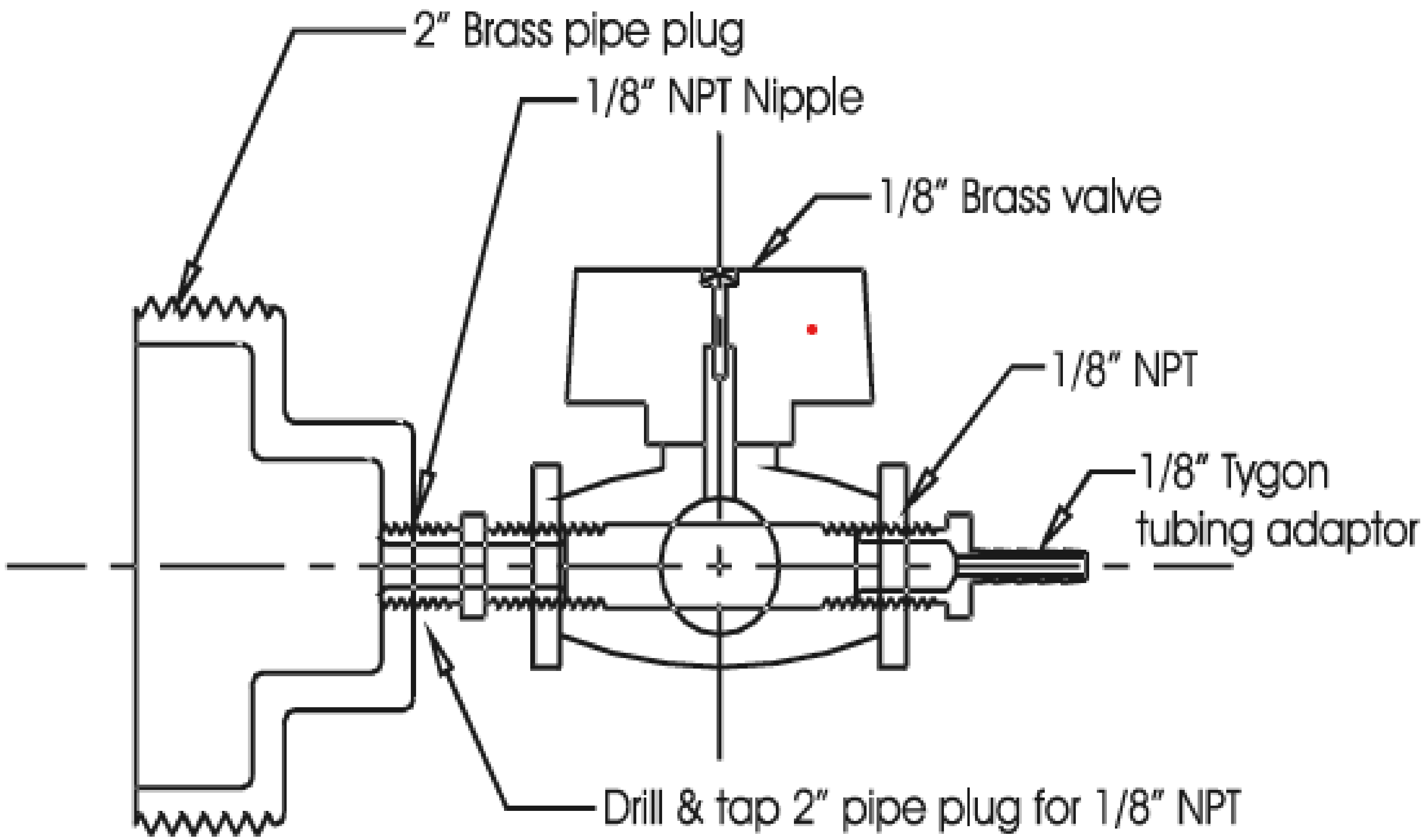
- It does not require a gas blanket and is effective on all mineral oil filled transformer designs.
- Reasonable equilibrium is required to collect all gases but occurs more quickly in oil than in the gas space.

DGA Sampling Techniques

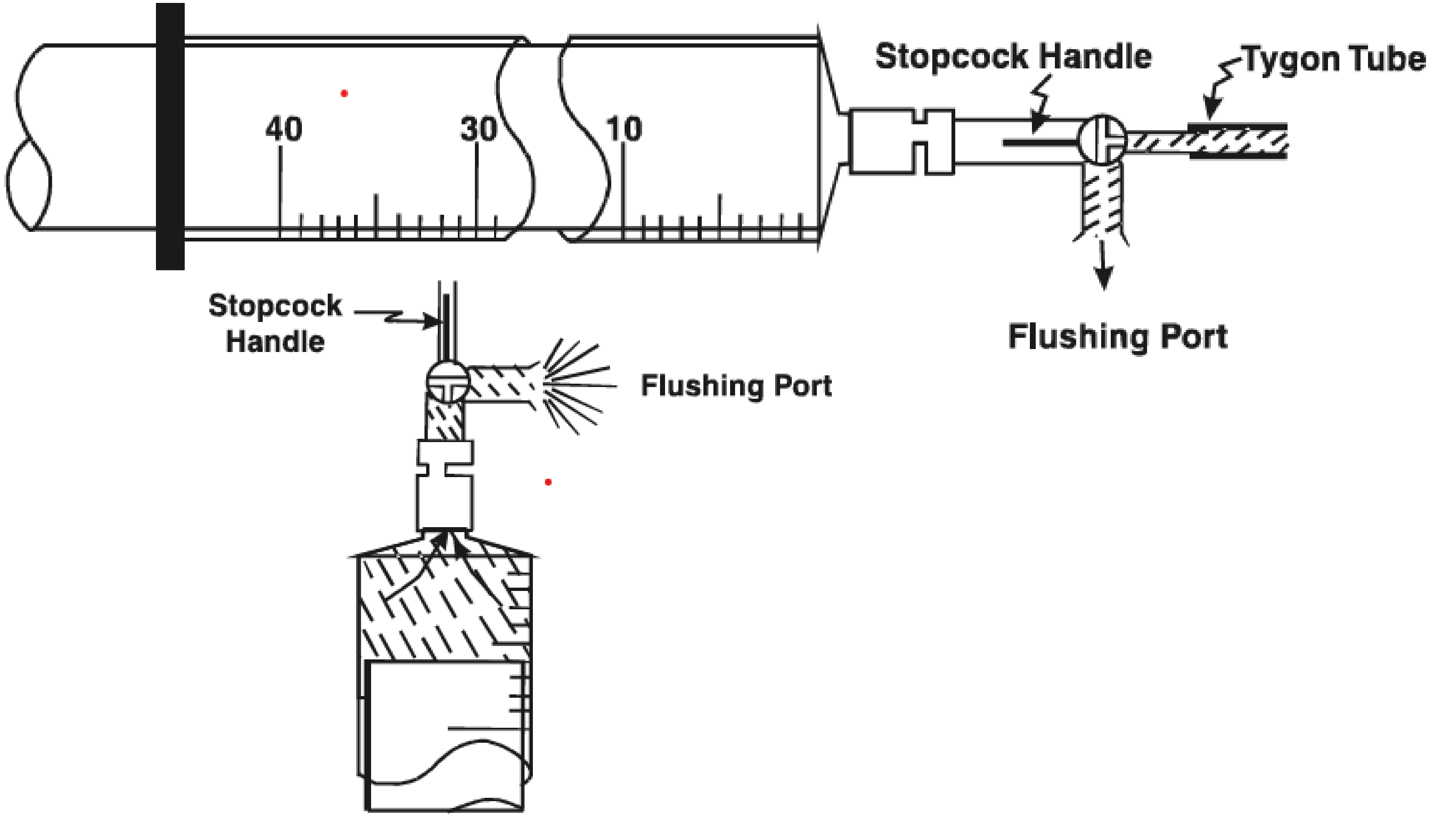
Extraction of samples are critical to accurate analysis:

- Verify positive head pressure at sample location
- Flush sample location, sampling lines, and collection syringe to get representative sample
- Use new sampling lines for each compartment or piece of equipment
- Verify use of clean, dry and sealed sampling devices required
- Remove all air from sample vessel
- Typically 30 mL samples are required for analysis
- Do not utilize plated or galvanized fittings

DGA Sampling Techniques



DGA Sampling Techniques



Dissolved Gas Analysis

It is possible to diagnose the type of transformer faults with analysis techniques such as:

- Ratio Codes
  - Doernenburg Ratios
  - Rogers Ratios/Three Ratio Code
  - Duval Triangle
  - Duval Pentagon
- Key Gas Standards
- IEEE Guidelines

Dissolved Gas Analysis

Doernenburg Ratio Codes

Doernenburg Ratios	Methane (CH_4) / Hydrogen (H_2)	Acetylene (C_2H_2) / Ethylene (C_2H_4)	Acetylene (C_2H_2) / Methane (CH_4)	Ethane (C_2H_6) / Acetylene (C_2H_2)
Suggested Fault Diagnosis				
Thermal Decomposition	> 1.0	< 0.75	< 0.3	> 0.4
Partial Discharge	< 0.1	Not Significant	< 0.3	> 0.4
Arcing	0.1 - 1.0	> 0.75	> 0.3	< 0.4

- Dissolved gas concentrations should exceed the IEEE Condition 1 values when utilizing this analysis technique
- If ratios do not fit within the values given for the diagnostic code, other analytical methods should be considered

Dissolved Gas Analysis

Rogers Ratio Codes

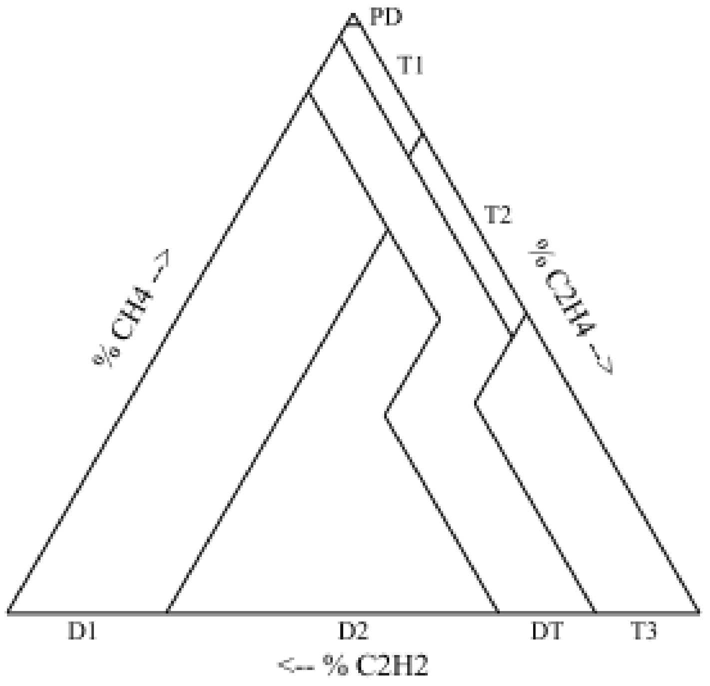
Rogers Ratios	Acetylene (C_2H_2) / Ethylene (C_2H_4)	Methane (CH_4) / Hydrogen (H_2)	Ethylene (C_2H_4) / Ethane (C_2H_6)
Suggested Fault Diagnosis			
Normal	< 0.1	> 0.1 - < 1.0	< 1.0
Partial Discharge	< 0.1	< 0.1	< 1.0
Arcing	0.1 - 3.0	0.1 - 1.0	> 3.0
Slight Thermal Fault	< 0.1	> 0.1 - < 1.0	1.0 - 3.0
Thermal Fault <700C	< 0.1	> 1.0	1.0 - 3.0
Thermal Fault >700C	< 0.1	> 1.0	> 3.0

If ratios do not fit within the values given for the diagnostic code, other analytical methods should be considered.

Dissolved Gas Analysis – Duval Triangle

Duval Triangle

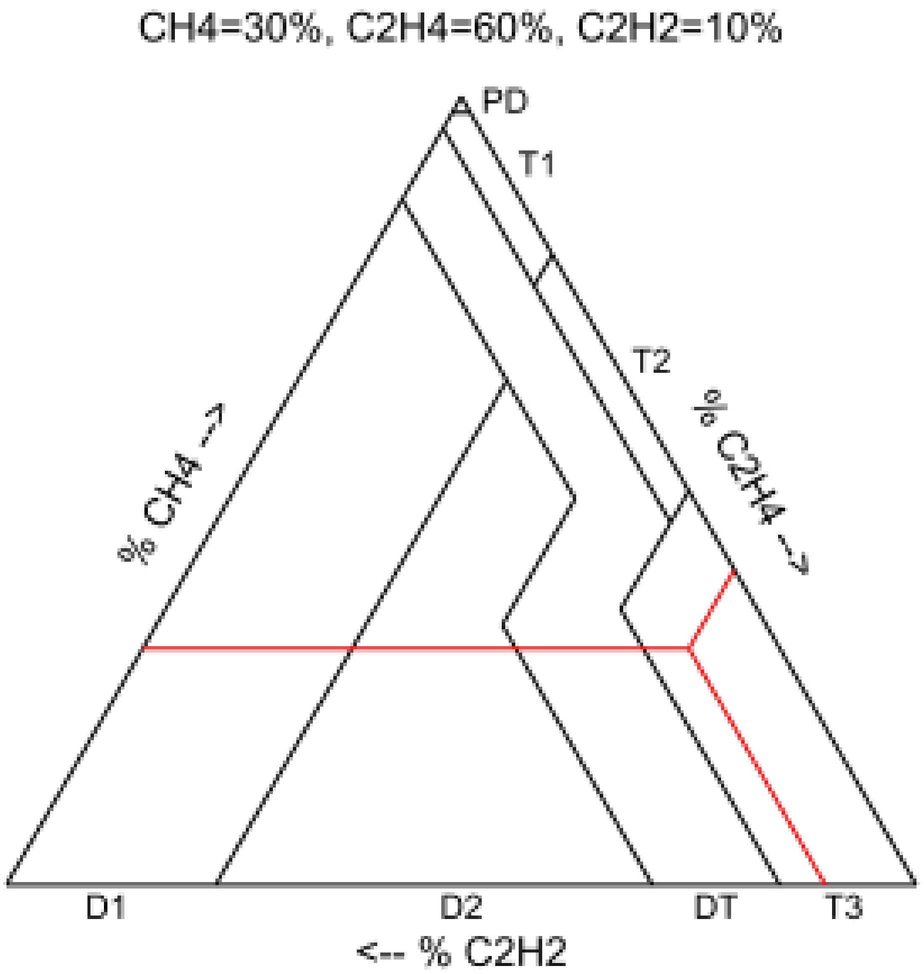
- Evaluates three gases – Methane (CH_4), Ethylene (C_2H_4), and Acetylene (C_2H_2) – as a percentage of the sum of the three gases
- Seven diagnostic triangles exist based upon type of fluid being analyzed and the type of oil compartment



FAULT CODES

PD	Partial discharge
T1	Low-range thermal fault (below 300 C)
T2	Medium-range thermal fault (300-700 C)
T3	High-range thermal fault (above 700 C)
D1	Low-energy electrical discharge
D2	High-energy electrical discharge
DT	Indeterminate - thermal fault or electrical discharge.

Dissolved Gas Analysis – Duval Triangle



FAULT CODES	
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D1	Low-energy electrical discharge
D2	High-energy electrical discharge
DT	Indeterminate - thermal fault or electrical discharge.

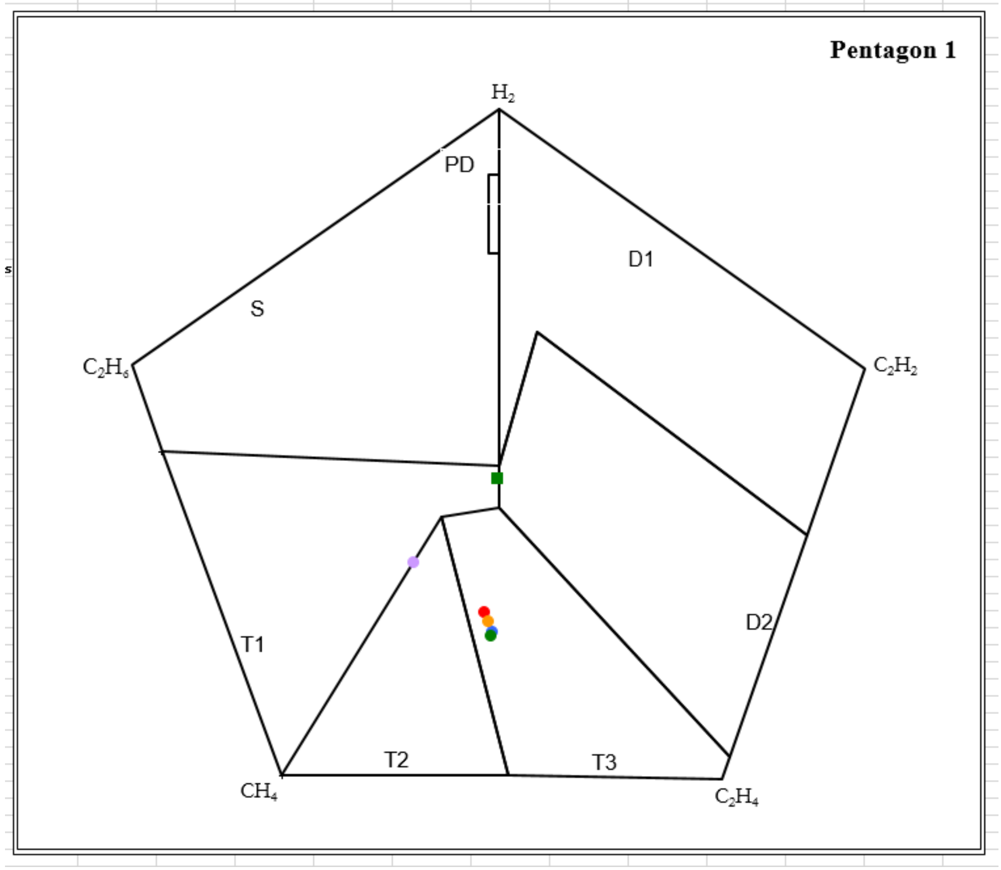
Dissolved Gas Analysis – Duvall Pentagon 1

Duval Pentagon

- Evaluates five gases – Hydrogen (H2) Methane (CH_4), Acetylene (C_2H_2), Ethylene (C_2H_4), and Ethane (C2H6)– as a percentage of the sum of the five gases

FAULT ZONES

PD:	Corona Partial Discharge
D1:	Discharges of Low Energy
D2:	Discharges of High Energuy
T3:	Thermal Fault > 300°C
T2:	Thermal Fault 300°C - 700°C
T1:	Thermal Fault < 300°C
S:	Stray Gasing of Oil < 200°C
O:	Overheating < 250°C
T3-H	T3 in Oil only
C:	Possible Carbonization of Paper



Dissolved Gas Analysis

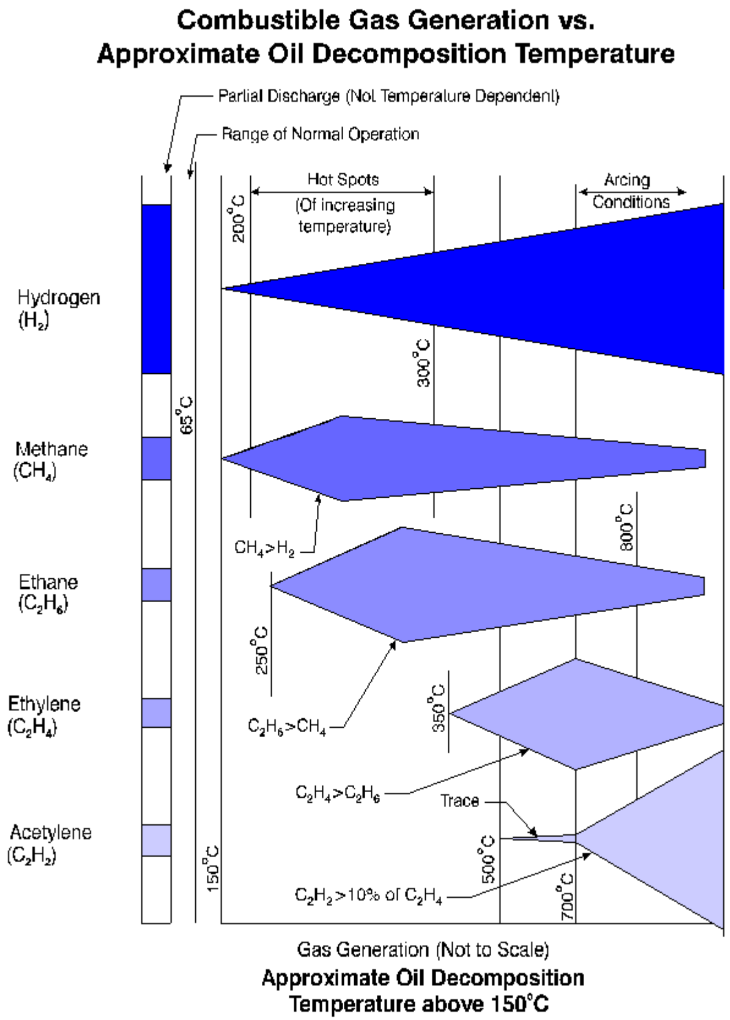
Key gas interpretation

Each "key" gas is identified with a certain type of fault

Fault Pattern	Key Gas
Conductor Overheating	CO/CO_2 (Carbon Oxides)
Oil Overheating	C_2H_4 (Ethylene)
Partial Discharge	H_2 (Hydrogen)
Arcing	C_2H_2 (Acetylene)

- The "key" gas is frequently the predominant gas
- occasionally another gas could be in high concentration
- Variations are possible because, over a wide range of temperatures
- Each gas attains a maximum generation rate at a certain temperature
- Depending on the temperature at the fault site, one of the other gasses may be in larger proportion

Gas Generation Temperatures



Combustible Gas Generation Versus Temperature.
Source : R.R. Rogers

Dominant Gas	Fault Temperature Range
Hydrogen (H2)	> 150 C
Methane (CH4)	>150 C
Ethane (C2H6)	>250 C
Ethylene (C2H4)	>350 C
Acetylene (C2H2)	>500 C

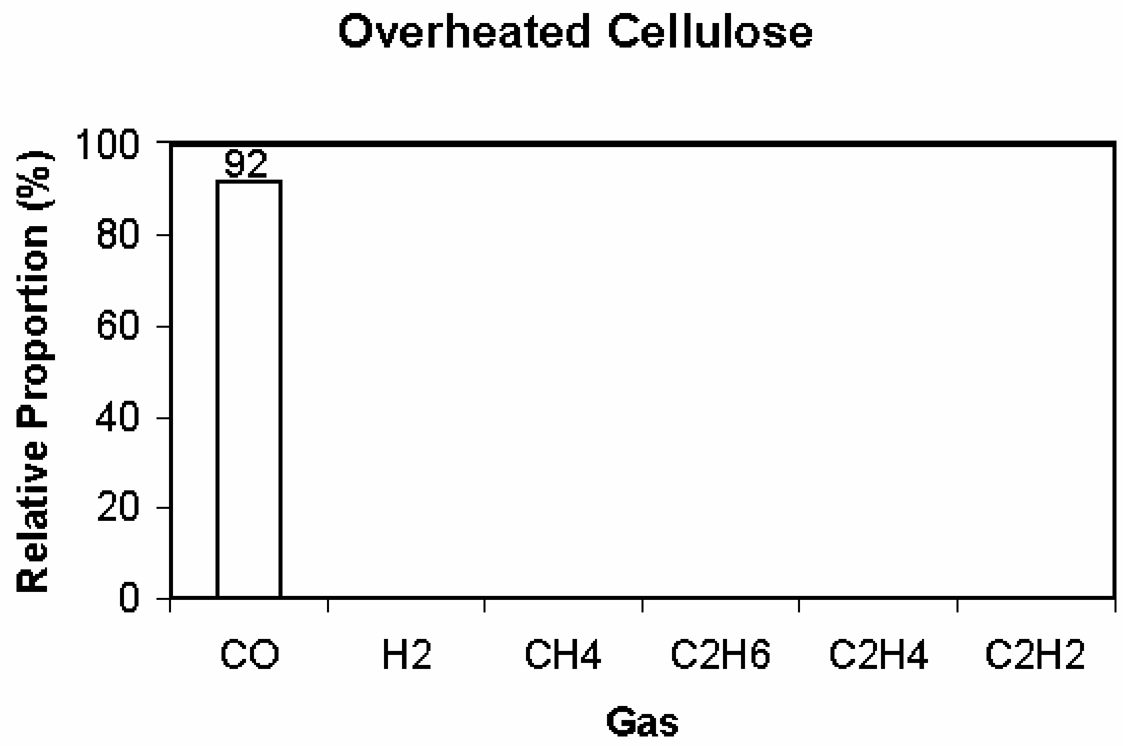
Dissolved Gas Analysis

- Thermal – Cellulose

  Large quantities of carbon dioxide and carbon monoxide are evolved from overheated cellulose (temperatures >110°C). Hydrocarbon gases, such as methane and ethylene, will be formed if the fault involves an oil-impregnated structure.

- Principle Gas: Carbon Monoxide

- Water is often a by product of the thermal decomposition.

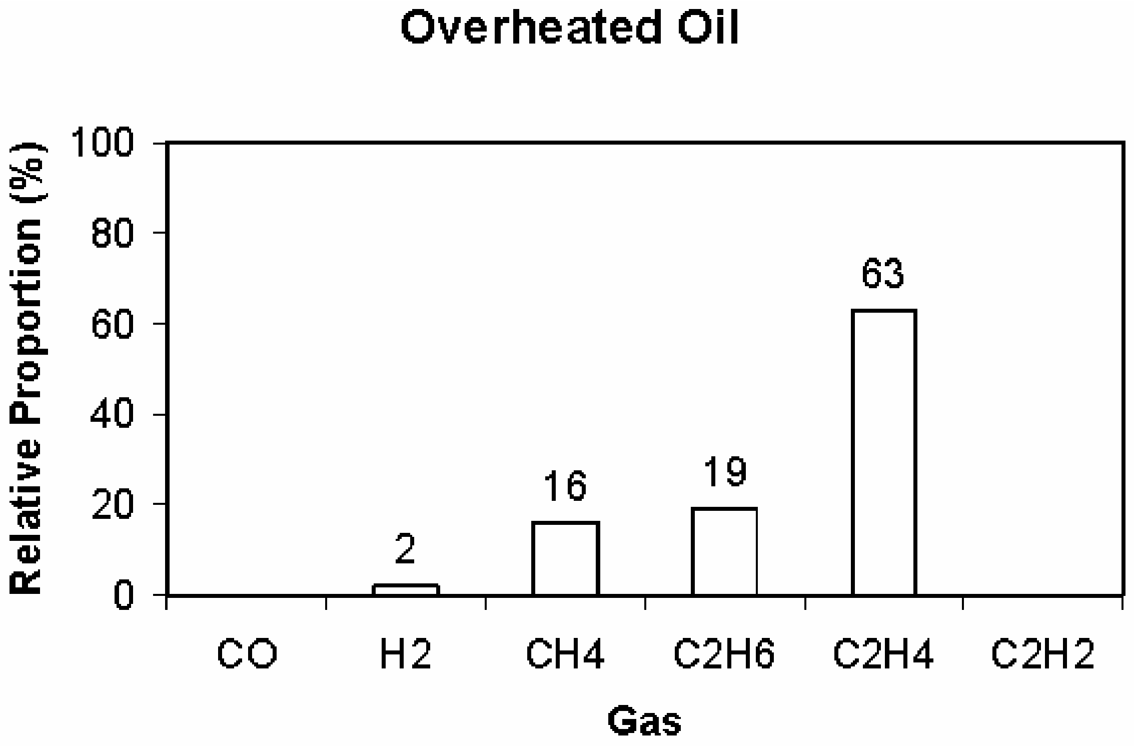


Dissolved Gas Analysis

- Thermal – 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

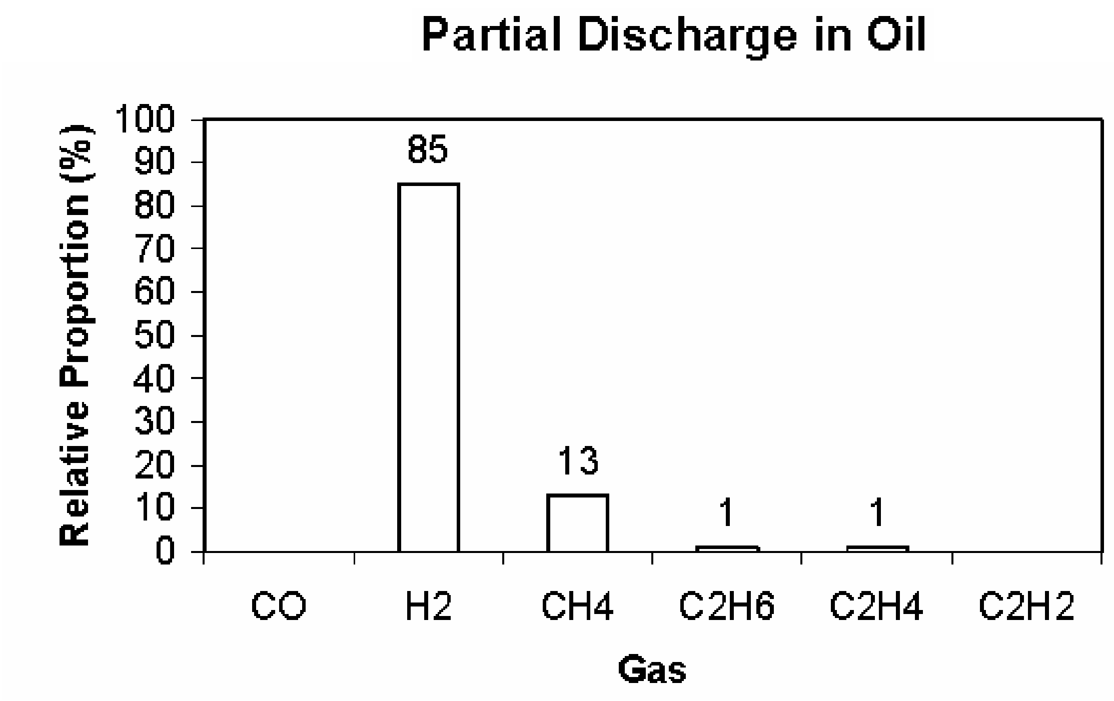


Dissolved Gas Analysis

- Electrical – Partial Discharge

  Low energy electrical discharges produce hydrogen and methane, with small quantities of ethane and ethylene. Comparable amounts of carbon monoxide and carbon dioxide may result from discharges in cellulose.

- Principle Gas – Hydrogen



Dissolved Gas Analysis

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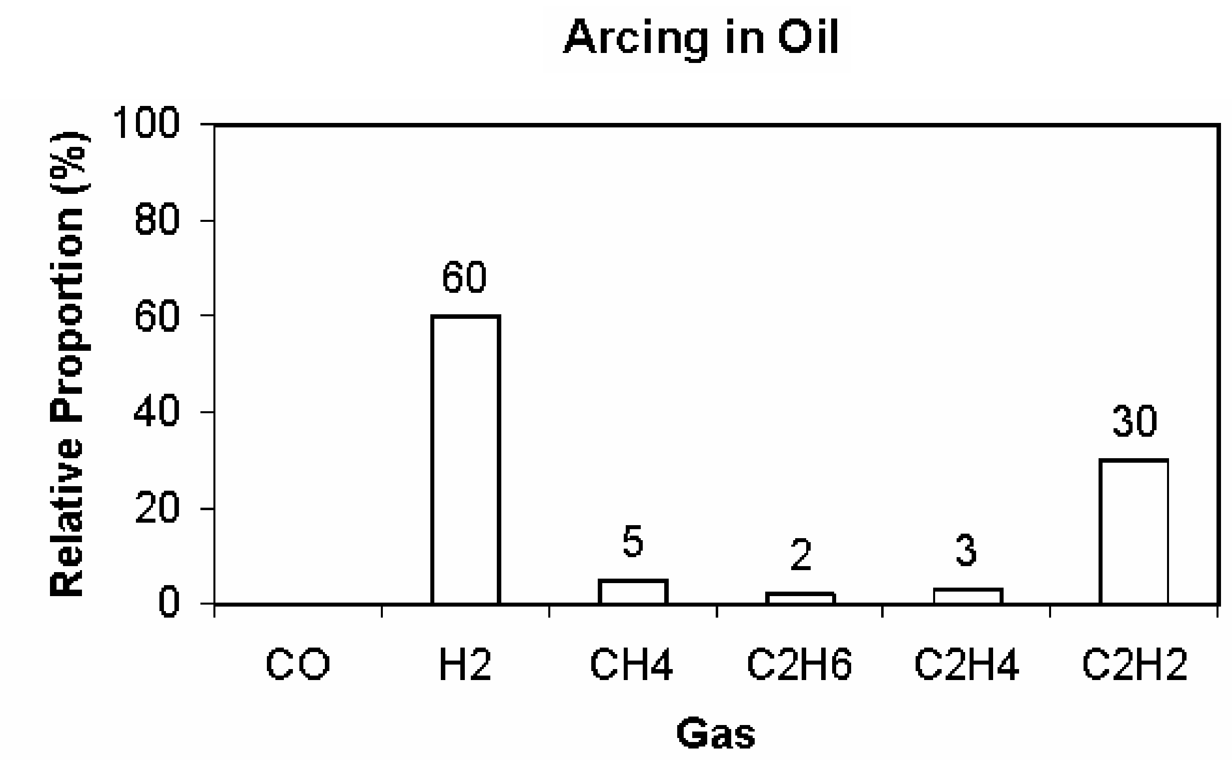
- Electrical – Arcing

  Large amounts of hydrogen and acetylene are produce, with minor quantities of methane and ethylene. Carbon dioxide and Carbon monoxide may also be formed if the fault involves cellulose. Oil may be carbonized.

- Principle Gas – Acetylene



Dissolved Gas Analysis

IEEE Guide for Interpretation of Gasses C57.104.2008

Condition	Dissolved Key Gas Concentration Limits (ppm)							
	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2	TDCG
1	100	120	1	50	65	350	2,500	720
2	101 - 700	121 - 400	2-9	51 - 100	66 - 100	351 - 570	2,501 - 4,000	721 - 1,920
3	701 - 1,800	401 - 1,000	10-35	101 - 200	101 - 150	571 - 1,400	4,001 - 10,000	1,921 - 4,630
4	>1,800	>1,000	>35	>200	>150	>1,400	>10,000	>4,630

Condition 1: TDCG below this level indicates satisfactory operation. Any individual combustible gas exceeding specified levels should prompt additional investigation.

Condition 2: TDCG within this range indicates greater than normal combustible gas level. Any individual combustible gas exceeding specified levels should prompt additional investigation. Action should be taken to establish a trend. Fault(s) may be present.

Condition 3: TDCG within this range indicates a high level of decomposition. Any individual combustible gas exceeding specified levels should prompt additional investigation. Immediate action should be taken to establish a trend. Fault(s) are probably present.

Condition 4: TDCG within this range indicates excessive decomposition. Continued operation could result in failure of the transformer.

Dissolved Gas Analysis

IEEE Guide for Interpretation of Gasses C57.104-2008

Condition	TDCG (ppm)	TDCG Rate (ppm/day)	Sampling Interval	Operating Procedure
4	>4630	>30	daily	Consider removal from service. Advise manufacturer.
		10 - 30	daily	
		<10	weekly	Exercise extreme caution. Analyze for individual gases. Plan outage. Advise manufacturer.
3	1921 - 4630	>30	weekly	Exercise extreme caution. Analyze for individual gases. Plan outage. Advise manufacturer.
		10 - 30	weekly	
		<10	monthly	
2	721 - 1920	>30	monthly	Exercise caution. Analyze for individual gases. Determine load dependence.
		10 - 30	monthly	
		<10	quarterly	
1	<=720	>30	monthly	Exercise caution. Analyze for individual gases. Determine load dependence.
		10 - 30	quarterly	Continue normal operation.
		<10	annually	

Important Reminders for Dissolved Gas Analysis

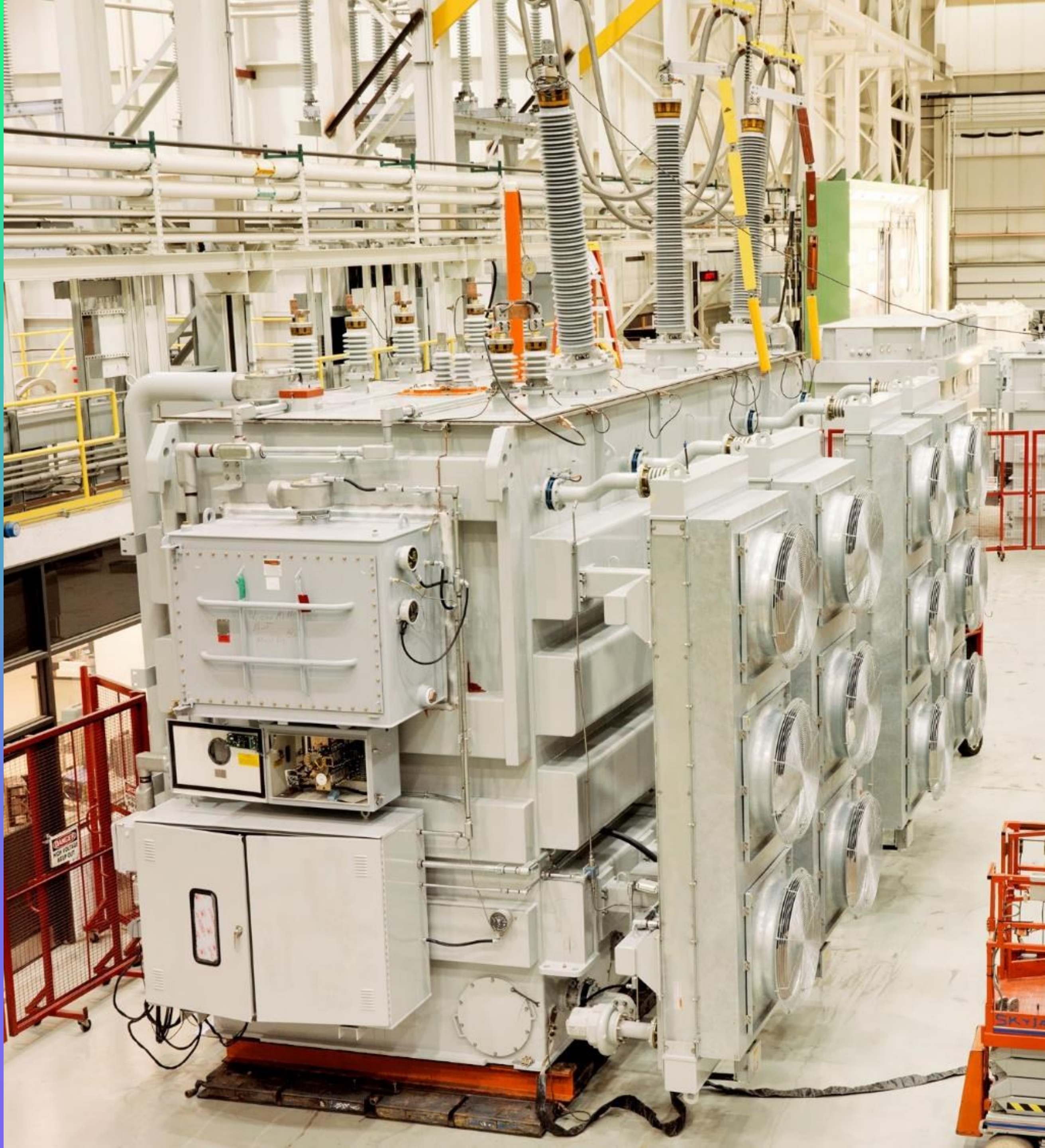
The effectiveness of dissolved gas analysis and of the interpretation of these analyses can be limited by:

- Sampling technique
- Testing – Low precision and repeatability between labs.
- Transformer's size and oil volume can distort the significance of gas concentration and generation rates.
- Temperature gradient in the active area can produce multiple source symptoms
- Stratification of the oil in the transformer can delay response to an incipient fault
- Lack of trend data
- Residual gas from past events
- Insufficient gas concentration to use ratio analysis

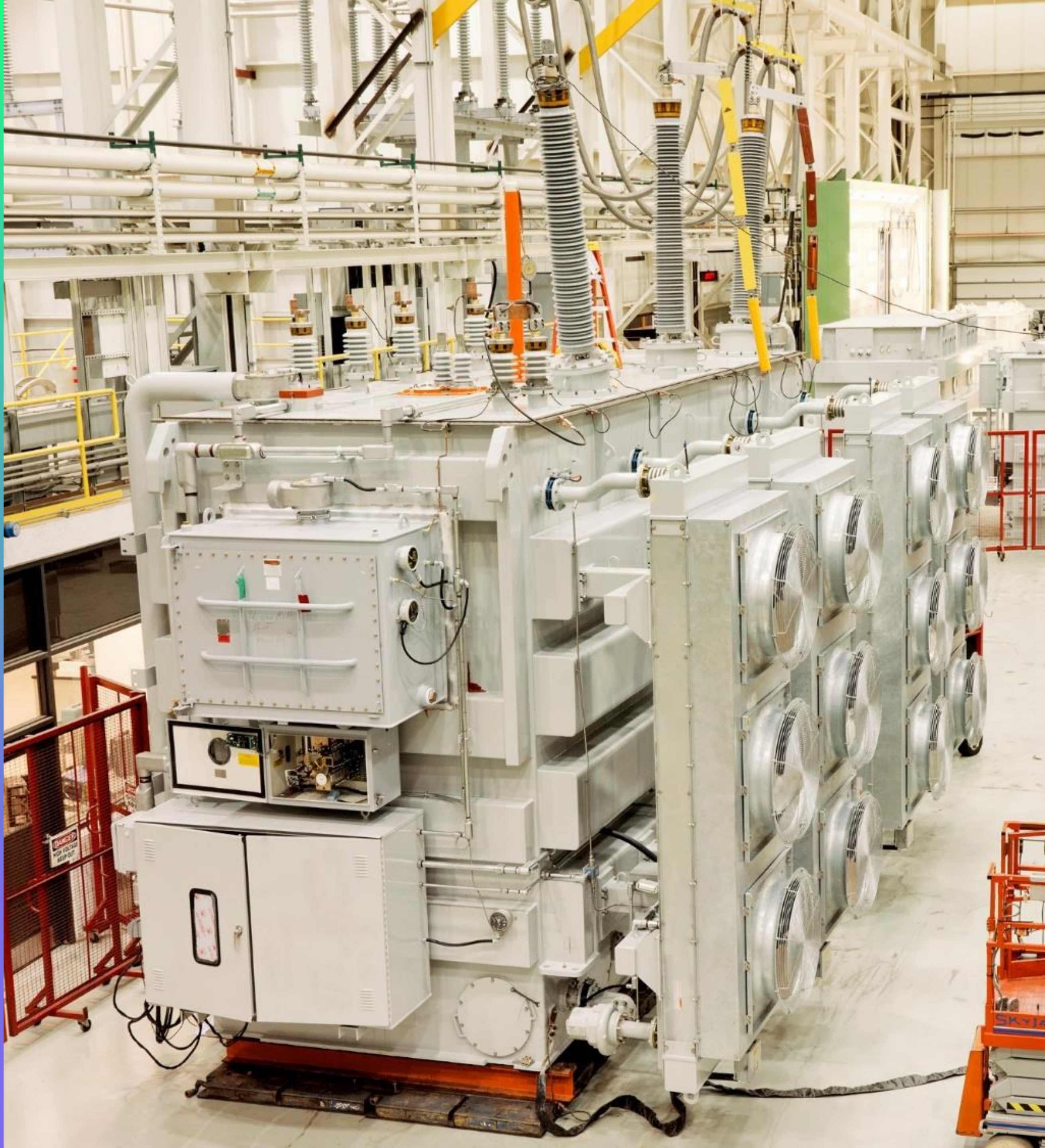
Test References

- IEEE Guide for Maintenance and Acceptance of Insulating Oil in Equipment (C57.106-2006)
- IEEE Guide for Interpretation of Gasses Generated in Oil Immersed Transformers (C57.104-2008)
- IEEE Guide for Dissolved Gas Analysis in Transformer Load Tap Changers (C57.139-2010)
- IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids (C57.147-2008)
- IEEE Guide for Interpretation of Gases Generated in Natural Ester and Synthetic Ester Immersed Transformers (C57.155-2014)

Post Fault Analysis



Minimum Testing After Fault



Transformer Trip Due to External Occurrence

A. OIL DGA TEST
   a) Analysis of results before re-energizing
B. Turns Ratio Testing 1L-16R

Events:

1. Overload
2. Ground
3. Lightning Arrestor Failure

Transformer Trip Due to Internal Occurrence

A. Oil DGA
B. Turns Ratio – Prefer HV DGA such as Doble Capacitor
C. Excitation
D. Power Factor – Windings and Bushings
E. Winding Resistance
F. Leakage Reactance – if Results unsatisfactory – followed by SFRA
G. Core Ground
H. SFRA

Types of Events:

1. Transformer Differential relay
2. SPR Operation
3. PRD Operation
4. Bushing Failure
5. Lightning Strike

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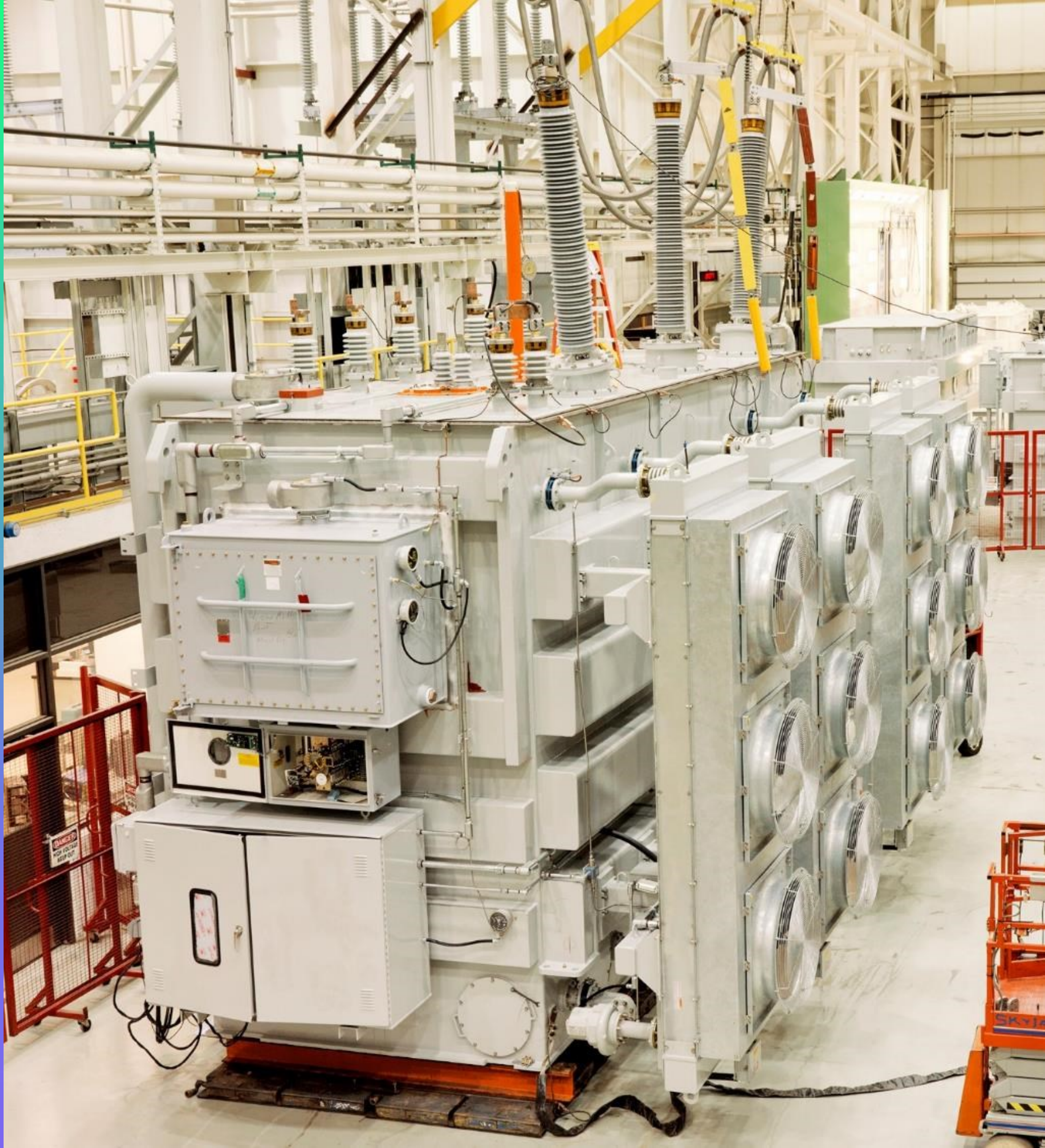
Internal Inspections – Warranted by Unsatisfactory Test Results



Internal Inspection

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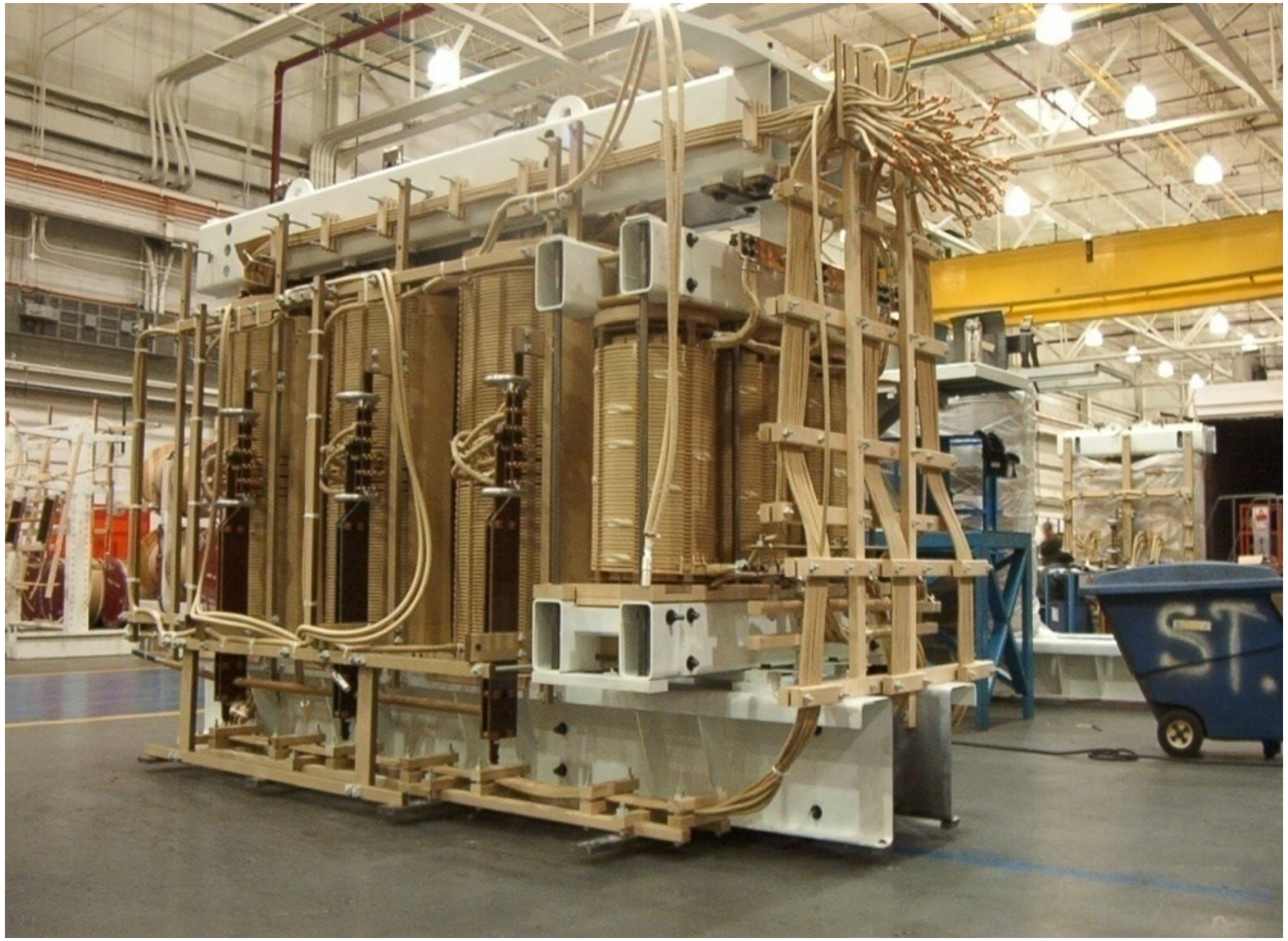
- Inspect tightness and alignment of coil spacers and blocks
- Inspect for shifting of core and coils
- Inspect for broken fiber or permali hardware
- Inspect phase barriers, oil boxes, and tank shielding



Clamping Systems

- Short circuit withstand capabilities can be compromised by less than designed clamping force. Clamping force can be reduced through the following:
  - Aging
  - Materials utilized
  - System Faults
  - Drying Operations
  - Transportation

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