Dissolved Gas-in-Oil Analysis for Preventative Maintenance of the Los Alamos Neutron Science Center (LANSCE) High Voltage Systems

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Outline

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- Safety Impacts of a Transformer Failure
- Life of a Transformer
- Purpose of Analysis

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- Quantitative Analysis
- Qualitative Analysis
- Rate of Rise Analysis
- Moisture Analysis
- Other Variables to Consider

III. **Results**
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- Rebuild Status
- IVR Rebuild History

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LANSCE High Voltage Power Supply for Radio Frequency (RF) Systems

13.2 KV AC →

Power from Substation

13.2 KV / 4160 V Transformer / Disconnect Switch

4160 V AC →

Vacuum Breaker Cabinet / Disconnect Switch

4160 V AC →

Inductrol Voltage Regulator

Variable output, depending on power required →

Transformer / Rectifier

Up to 90 KV DC →

Power to capacitor room. Each capacitor room feeds 6 to 7 RF systems

Safety Impacts of a Transformer Failure

Combustible gasses + fuel + spark →

Hydrogen, Methane, Acetylene, Ethane, Ethylene, Carbon Monoxide

TRs = 2016 gallons of oil
IVRs = 590 gallons of oil

Arcing

Catastrophic Failure

(not at LANL)

We mitigate catastrophic failures by:

- Doing annual dissolved gas analysis.
- Processing units with increasing gas levels.
- Rebuilding units to fix the source of gassing problems.
- Taking units out of service if combustible gasses are greater than 10% total gasses.

The Life of a Transformer

- **Transformer failure ➔ Failure of the paper insulating material**

  Mechanical failures of paper insulation account for 85% of transformer failures.

- **Paper is weakened by four conditions:**

  1. **Heat** -Operating oil temperatures 8 ˚C above the design temperature (i.e., 95 ˚C at the top of oil and 110 ˚C at hot spots) will half the life of the paper.
  2. **Oxygen** - Paper with low oxygen (~ 300 ppm) will have 10 times the life time of paper with high oxygen (~ 3000 ppm).
  3. **Moisture (Water)** - Doubling the percentage of moisture will half the life.
  4. **Oxidation Products** - Acidity in the oil above 0.05 mg/KOH/g oil from oxidation decay products significantly reduces the strength, thus life, of the paper.

- **Design Life of Transformers**
  - The design life of large oil filled transformers is 25-30 years. After an age of 30 years, the failure probability significantly increases.
  - The transformers at LANSCE are 45 years old. Older transformers tend to have a longer life because computer codes were not yet available as design tools. Thus, they were designed more conservatively.

➔ Predictive maintenance is critical to keep the units operating reliable.

Purpose – Why do this analysis?

1. **To keep units operating reliable and minimize downtime.**
   - This analysis enables us to do predictive maintenance rather than corrective maintenance.
   - It costs $60,000 and 3 to 5 days of lost beam time to install and condition a spare unit.
   - If a good spare is not available, it will take about 9 months to refurbish the unit.
2. **LANSCE-RM Project funded an IVR and TR rebuild for 3 years**
   - LANSCE - Risk Mitigation (RM) Project funded an IVR and TR rebuild for 3 years.
   - This project was initially going to fund 5 TR rebuilds and 7 IVR rebuilds, but funding was lost for the project.
   - This analysis is the basis for selecting the next rebuild candidate.
   - Funding was obtained for a fourth IVR rebuild in 2015 through LANL institutional funds.

IEEE Limits for Dissolved Gasses in Transformer Oil

- Gasses above the accepted limit are an indication of arcing, paper degradation, corona and thermal heating.
- Hydrogen and methane are emitted at 110 °C
- Ethane emitted at 150 °C
- Ethylene emitted at 300°C
- Acetylene emitted at 700 °C

Gas	IEEE Limit* (ppm)	Interpretation
Hydrogen (H_2)	100	Arcing, Corona, Cellulose Degradation
Methane (CH_4)	120	Sparking, Local Overheating
Ethane (C_2H_6)	65	Local Overheating
Ethylene (C_2H_4)	50	Severe Overheating
Acetylene (C_2H_2)	1	Electrical Arcing
Carbon Monoxide (CO)	350	Severe Overheating
Carbon Dioxide (CO_2)	2500	Severe Overheating
Total Dissolved Combustible Gas	720	Severe Decomposition

* IEEE Standard C57.104-1991 Revision Draft

Qualitative and quantitative analysis are done annually on the transformer rectifiers (TRs) and Inductrol Voltage Regulators (IVRs).

Quantitative Gas Analysis

Method 1

- Individual gas levels were compared to IEEE limits ➔ a color cell label and score were assigned to each gas as follows:
  - Red (1 point) – significantly above IEEE limits
  - Yellow (1/2 point) – near the limits or on a upward trend approaching IEEE limits
  - Green (0 points) – below limits
- A Health Label is assigned to each unit based on the total score

Total Score:		
5 <=	Score	
4 <=	Score	< 5
1 <=	Score	< 4
0 <	Score	< 1

Method 2

- Same as Method 1 except that certain gasses (acetylene, ethylene and CO) were weighted more because these gasses typically indicate more severe problems.

Method 3

- Individual gas levels were compared to IEEE limits ➔ Current gas values were divided by IEEE standard to determine a ratio. Points were assigned as follows based on the value of the ratio:
  - 7 < ratio ➔ purple cell label (2 points)
  - 4 < ratio < 7 ➔ red cell label (1 point)
  - 1 < ratio < 4 ➔ yellow cell label (1/2 point)
  - Ratio < 1 ➔ green cell label (0 point)

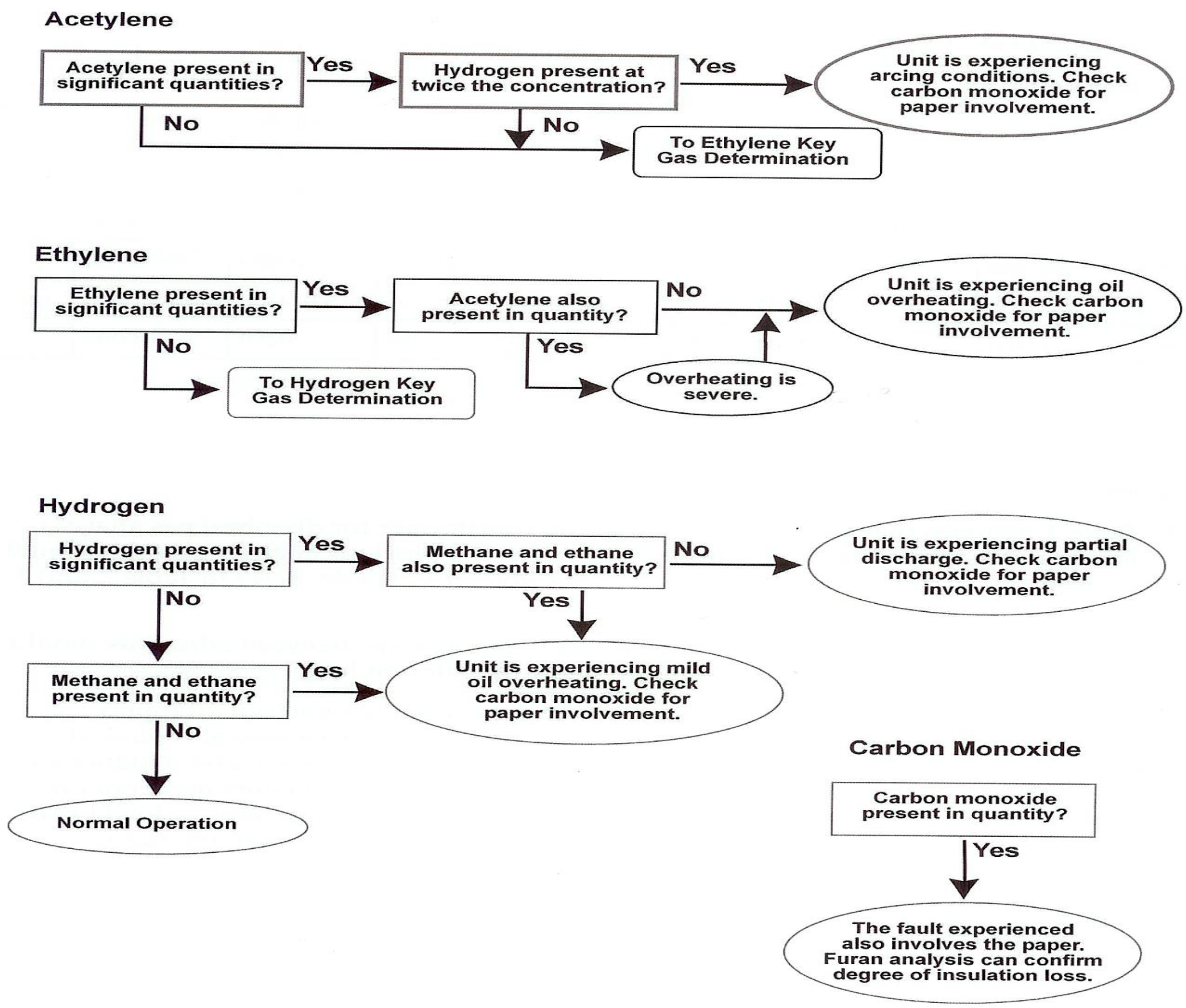
Quantitative Gas Analysis - Example

IVRs

201 MHz	Hydrogen (H_2)	Methane (CH_4)	Acetylene (C_2H_2)	Ethane (C_2H_6)	Ethylene (C_2H_4)	Carbon Monoxide (CO)	Carbon Dioxide (CO_2)	Total Combust. Gas
Module 1								
Module 2								
Module 3								
Module 4								
805 MHz								
Sector B								
Sector C								
Sector D								
Sector E								
Sector F								
Sector G								
Sector H								
Spares								
201 spare mod 1 IVR								
Spare 805 IVR								

	Reds (1 point)	Yellow (1/2 point)	Total Score
Module 1	0	0	0
Module 2	0	0	0
Module 3	0	0	0
Module 4	0		0
Sector B	0	0	0
Sector C	0	0	0
Sector D	0	0	0
Sector E	2	3	3.5
Sector F	0	2	1
Sector G	0	0	0
Sector H	0	0	0
201 spare mod 1 IVR	0	0	0
Spare 805 IVR	0	0	0

Qualitative Gas Analysis Method



Example of Qualitative Gas Analysis Results

Location	Elevated Gas	Qualitative Analysis Conclusion
Module 2 TR	O_2 and N_2	Air leak
Module 3 TR	O_2 and N_2	Air leak
Module 4 TR	O_2 and N_2	Air leak
Sector B TR	Acetylene, hydrogen, O_2 and N_2	Arcing (700 Deg C) and air leak
Sector D TR	Hydrogen, CO_2, O_2 and N_2	Partial discharge and air leak.
Sector F TR	Acetylene, hydrogen, CO_2, O_2 and N_2	Arcing (700 Deg C) and air leak
Sector G TR	Ethylene, ethane, H_2, O_2 and N_2	Infrequent mild overheating (300 Deg C)
ETL 201 TR	Acetylene	Arcing (700 Deg C)
Mod 1 IVR	CO, hydrogen	Mild overheating (300 Deg C), paper involvement
Mod 2 IVR	O_2 and N_2	Air Leak
Mod 3 IVR	O_2 and N_2	Air Leak
Mod 4 IVR	CO, methane	Mild Overheating (300 Deg C)
Sec B IVR	H_2, methane, ethane, ethylene, CO	Overheating (300 Deg C), paper involvement
Sec C IVR	H_2, methane, ethane, ethylene, CO, O_2	Overheating (300 Deg C), paper involvement
Sec D IVR	H_2, methane, ethane, CO	Overheating (300 Deg C), paper involvement
Sec E IVR	H_2, methane, ethane, ethylene	Overheating (300 Deg C)
Sec F IVR	H_2, methane, ethane, ethylene	Overheating (300 Deg C)
Sec G IVR	methane, ethane, ethylene	Mild Overheating (300 Deg C)

Rate of Rise Analysis

1) The rate of gas generation (rate of rise) was calculated, in parts per million (ppm) per day.

2) The time it will take the unit to reach the IEEE standard was predicted based on a <u>linear rate</u> of rise.

1 year < time to reach IEEE standard ➔ purple cell label
1 year < time to reach IEEE standard < 3 years ➔ red cell label
3 years < time to reach IEEE standard < 7 years ➔ yellow cell label
time to reach IEEE standard > 7 years ➔ green cell label

3) A rate of rise score was calculated by assigning points to each individual gas as follows:

- Acetylene, Ethylene and CO - 2 points
- Purple 1 ½ points
- Red – 1 point
- Yellow – ½ point
- Green – 0 point

4) Health Label for each unit was applied based on the score as follows:

Total Score:		
6.5 <=	Score	
5 <=	Score	< 6.5
1 <=	Score	< 5

Example of Rate of Rise for the IVRs

IVRs

201 MHz	Hydrogen (H2)	Methane (CH4)	Acetylene (C2H2)	Ethane (C2H6)	Ethylene (C2H4)	Carbon Monoxide (CO)	Carbon Dioxide (CO2)	Total Combust. Gas
Module 1	3.38	15.41	3.48	-8.83	5.09	9.79	NA	4.65
Module 2	31.34	25	8	9.5	NA	-1	NA	220
Module 3	11	-1	-4.62	-3.26	-11.56	-9.4	NA	-7.03
Module 4	19.7	1.48	-2.09	0.38	-4.13	-2.5	NA	-6.28
805 MHz								
Sector B	1.21	1.16	-2.15	-0.45	3.18	3.07	NA	5.15
Sector C	1.28	1.31	1.75	4.38	3.64	2.18	NA	1.75
Sector D	1.45	2.61	1.23	1.76	6.37	2.45	NA	1.68
Sector E	-0.09	-0.87	0.72	1.28	-0.32	-1.01	NA	-0.44
Sector F	1.19	0.42	1.86	3.82	1.57	0.38	NA	0.98
Sector G	5.64	1.54	2.69	-1.94	5.39	5.22	NA	3.25
Sector H	19.45	13.76	5.34	20.31	-53.49	NA	NA	9.34
Spares								
Spare805	-20.07	-8.08	30.1	-249	-23.13	-6.17	NA	-43.32
ETL 805	3.22	111.85	1.54	0.41	-61.27	22.37	NA	3.34

	Acetylene, Ethylene and CO (2 points)	Purples (1 1/2 point)	Reds (1 point)	Yellow (1/2 point)	Total Score
Module 1	2			2	5
Module 2					0
Module 3					0
Module 4		1	1		2.5
805 MHz					0
Sector B	1		2	2	5
Sector C	2		3	2	8
Sector D	2			4	6
Sector E	1		1		3
Sector F	2	2	2	1	9.5
Sector G	2		1	3	6.5
Sector H	1				2
Spares					0
Spare805	1		1	1	3.5
ETL 805	1	1		2	4.5

Moisture Analysis

- In 2009 a Drymax unit was purchased to address the moisture issue.

- This unit slowly removes the moisture from the oil. (2 gpm flow rate)

- An equilibrium of moisture between the oil and the paper is established by removing moisture from the paper.

- This process takes 3 to 4 months.

- The moisture analysis is used to determine which unit to move the Drymax unit to next.

Transformer Rectifiers		
Unit	% Moisture	Grade
Module 1	3.84	D
module 1 rec	0.75	A
Module 2	1.3	B
Module 3	0.62	A
Module 4	0.48	A
Sector B	0.6	A
Sector C	1.14	A
Sector D	0.91	A
Sector E	0.78	A
Sector F	0.55	A
Sector G	1.09	A
Sector H	0.68	A
ETL 805 TR	1.02	A
201 Spare mod 1 Tran	0.6	A
ETL 201 TR	1.93	B
201 spare mod 1 rec	1.09	A
Spare 805 TR	0.75	A

Annual Processing and Repair Work

- Every year, a subcontractor is hired to come on site to process units and perform repairs to units as budget allows.
- The processing reduces the amount of compostable gasses in units and thus reduces the rate of oxidation.
- Repairs focus on reducing air leaks which have the potential to increase oxidation.
- Repairs focus on reducing oil leaks with an environmental compliance impact.

Hoses from IVR …

to oil processing rig

Heaters

Oil Processing Unit

Vacuum Pump

Filters

Other Variables Considered:

Furans, acid test, interfacial tension and operating temperature

Furans:

- When paper breaks down depolymerization occurs. Depolymerization releases water and furans. Furans are products of paper decomposition.
- All 5 furans eventually breakdown to 2FAL. If the other 4 furans are present, this can be an indication that there is an active condition breaking down the paper.
- The total furan levels can be an indicator of the % life remaining in the paper. The total furan levels are not included in the analysis because every time the oil is processed, the furans are removed.

Acid Test:

- The acid test and interfacial tension test results are not included in the analysis because all the results were acceptable. (Both of these tests measure the oxidation of oil).

Temperature:

- The operating temperature is recorded every other week and trended to verify that no units are operating hot.

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- The operating temperature is recorded every other week and trneded to verify that no units are operating hot.

Other Variables Considered: Current PCB Levels

- Transformer Rectifiers:

TC	Unit	PCB (ppm)
1	Module 1	ND
31	module 1 rec	ND
3	Module 2	ND
5	Module 3	2
7	Module 4	ND
10	Sector B	ND
24	Sector C	ND
14	Sector D	ND
16	Sector E	27
18	Sector F	ND
20	Sector G	22
22	Sector H	ND
12	805 spare TR	4
26	ETL 805 TR	2
28 & 30	spare 201 rec & trans	ND
29	ETL 201	ND

- **ND = none detected**
- **(< 2mg/kg per ASTM D4059)**
- **Non PCB < 50 ppm**
- **50 ppm < PCB Contaminated < 500 ppm**
- **PCB = polychlorinated biphenyls**

- Inductrol Voltage Regulato

TC	Unit	PCB (ppm)
2	Module 1	53
4	Module 2	49
6	Module 3	15
8	Module 4	9
9	Sector B	7
11	Sector C	13
13	Sector D	12
15	Sector E	20
17	Sector F	ND
19	Sector G	8
21	Sector H	2
23	Spare 805 IVR	10
25	ETL 805 IVR	5
27	spare 201 ivr	2

Other Variables Considered: Current PCB Levels

Units of Concern:

- Module 1 IVR (194 gallons)

PCB CONTENT EXPRESSED IN PPM

DATE	1242	1254	1260	OTHER	TOTAL
03/14/95	143		16		159
10/12/00	3				3
11/22/10	24	11			35
08/05/14	40	13			53

COLOR LABEL: Orange **CLASS:** PCB CONTAM

Results in mg/kg
ND means None Detected
(<2 mg/kg per ASTM D4059)

- Module 2 IVR (590 gallons)

PCB CONTENT EXPRESSED IN PPM

DATE	1242	1254	1260	OTHER	TOTAL
03/14/95		9			9
11/22/10		34			34
08/05/14		49			49

COLOR LABEL: Orange **CLASS:** PCB CONTAM

Results in mg/kg
ND means None Detected
(<2 mg/kg per ASTM D4059)

Example of Analysis Summary

TC #	IVRs	Method 1	Method 2	Method 3	Rate of Rise	Moisture	Qualitative Analysis
2	Module 1						
4	Module 2						
6	Module 3						
25	Module 4						
17	Sector B						
11	Sector C						
13	Sector D						
15	Sector E						
23	Sector F						
19	Sector G						
21	Sector H						
9	Spare 805 IVR	Out for Rebuild					
8	ETL 805 IVR	Out for Repair					
27	201 spare mod 1 IVR						

Summary of Rebuild Priority and Status

IVR Rebuild Priority, Reason for Rebuild and Status:

1. ~~Sector F IVR (TC#17), Severe Overheating~~, complete 2012
2. ~~Sector E IVR (TC#15), Severe Overheating~~, complete 2014
3. ~~Sector B IVR (TC#9), Mild Overheating~~, complete 2013
4. Sector D IVR (TC#13), Severe Overheating, arcing, candidate for 2016
5. Sector G IVR (TC#19), Severe Overheating
6. Sector C IVR (TC#11), Mild Overheating
7. Sector F IVR (was spare) (TC#23), significant Overheating, being rebuilt in 2015
8. Module 1 IVR (TC#2), Mild Overheating
9. Module 2 IVR (TC#4), Mild Overheating
10. ~~Module 4 IVR, Mild Overheating~~, complete 2012

TR Rebuild Priority, Reason for Rebuild and Status:

1. ~~Module 1 TR spare (TC28/30), Arcing/overheating, suspect history~~, complete 2012
2. ~~Sector F TR (TC#12), Arcing~~, complete 2014
3. Sector E TR (TC#16), Significant Overheating, Arcing, next rebuild candidate
4. ~~Sector B TR (TC#10), Arcing~~, complete 2013
5. Sector D TR (TC #14), Overheating
6. Module 2 TR (TC #3), Overheating, possibly FY16
7. Sector G TR (TC #20), Over heating
8. ~~Sector F TR, was spare before, (TC#18)~~ Complete 2012

As found condition of IVRs that were rebuilt

- The 2009 DGA showed a problem the following IVRs: Sector F, B, E, D, G, C and Spare
- We found the following conditions in the IVRs upon tear down at vendor:


Sector H IVR 2007


Sector F IVR 2012


Sector B IVR 2013


Sector E IVR 2014

- The 2013 DGA analysis shows Sectors D, G and C IVRs have VERY similar DGA results! This project is to rebuild Sec D in FY15. Since we have 4 case studies to prove it, we are certain of the failure mechanism and what the inside of the IVR looks like.

Conclusions and Path Forward

Conclusions:

- The DGA analysis has been a correct indicator of a problem in the unit.
- It is critical to carefully monitor the health of the units to ensure a high reliability of the units.
- Even though these transformers are 45 years old, they can still perform reliable.

Path Forward:

- Continue with the annual DGA testing and analysis. Evaluate the results and adjust the rebuild priorities and list if required.
- Continue with the annual processing of units with high gas levels.
- Continue with the operation of the Drymax unit to remove moisture.
- Continue with the annual leak repair and maintenance program.
- Rebuild / rewind IVRs at a rate of 1 per year as funding allows.
- Try to obtain funding for TR repairs, even if it is reduced scope.