INVESTIGATING COPPER SULFIDE CONTAMINATION IN A FAILED LARGE GSU TRANSFORMER

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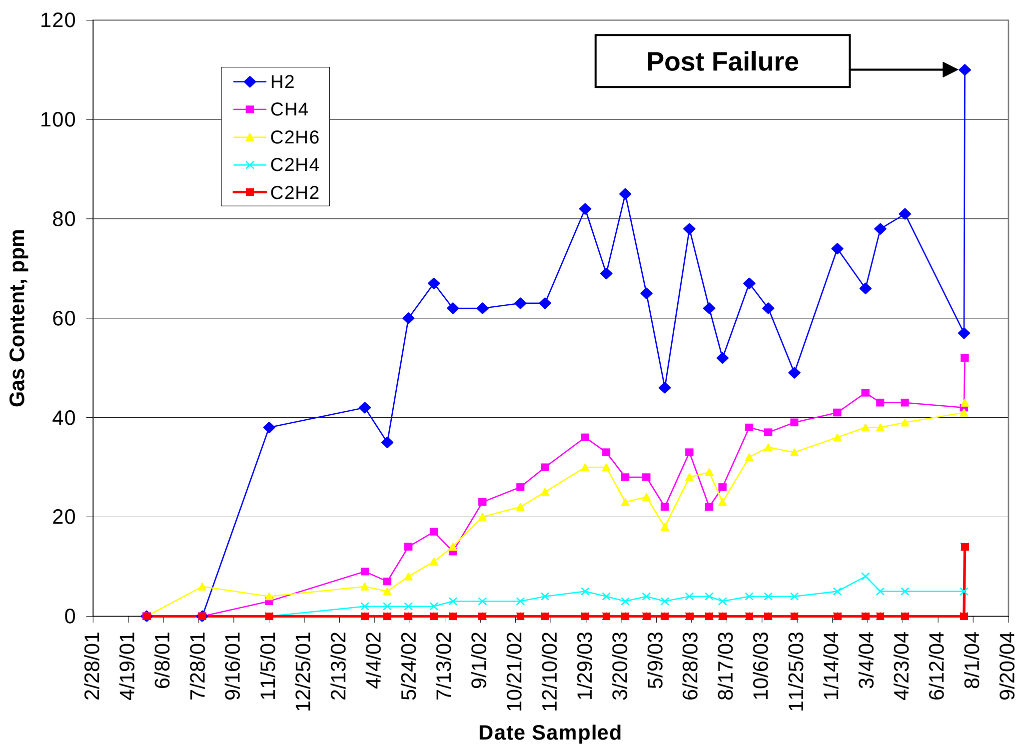
INTRODUCTION

This paper discusses some of the details of the teardown and laboratory investigation of a failed GSU transformer. The failure involved sulfide contamination of the copper conductor and copper sulfide in the associated paper insulation in the upper third portion of the failed winding. The theory is put forth that a combination of time and temperature and corrosive sulfur in the oil created conditions to exist in the transformer that caused this problem despite the oil having passed the standard test criteria for corrosive sulfur. Although the mechanism is still unclear, copper ions migrate to the insulating paper adjacent to the conductor, react with corrosive sulfur compounds, and cause a reduction in dielectric strength. At some point, the voltage being carried by the conductor exceeds the insulating capacity of the paper insulation and BIL rating of the transformer. The result is arcing between two or more disks and a subsequent burn through (failure).

FAILURE EVENT AND HISTORY

Without notice, a large GSU transformer failed in July of 2004. In reviewing the operating history of the transformer including loading, transients and other operating parameters there was nothing noteworthy or unusual in its 4 years of service. A review of the historical oil quality data showed that the oil was in good condition and the unit was very dry. Dissolved gas-in-oil analysis (DGA) was performed routinely over the course of its in-service life and there was no indication of an impending failure. The DGA results were so normal in fact, that even though the unit was sampled the day before the failure (7/19/04), totally by coincidence, there was no indication of impending failure as shown in Figure 1.



Gassing Trend of GSU Transformer
FIGURE 1

The gassing pattern is a typical one for GSUs in that there are some heating gases present but not of sufficient concentration to raise any alarms or take remedial action. A sample taken the day before the failure actually shows a slight decrease in combustible gases (Figures 1 and 2) and still significantly far below any level that would be of concern. The acetylene content of 14 ppm would be of concern but that was only present after the failure occurred.

Total Combustible (TCG) and Acetylene (C_2H_2) Gas Content

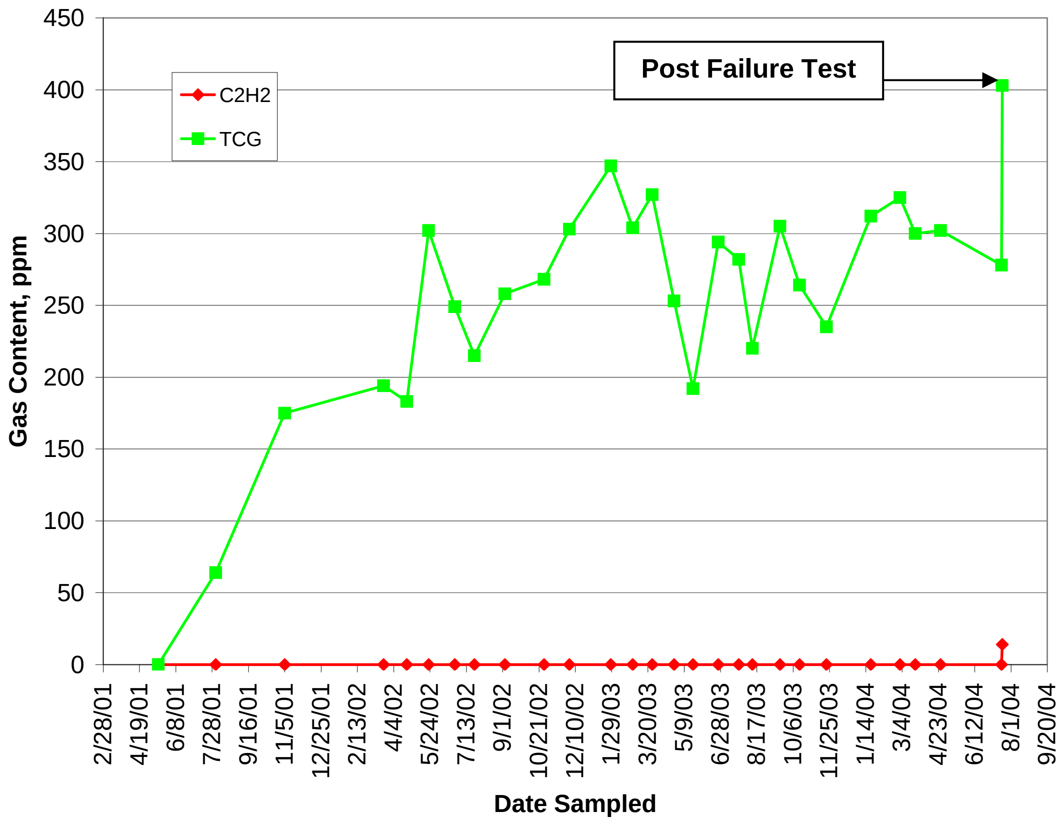


FIGURE 2

INSPECTION AFTER FAILURE

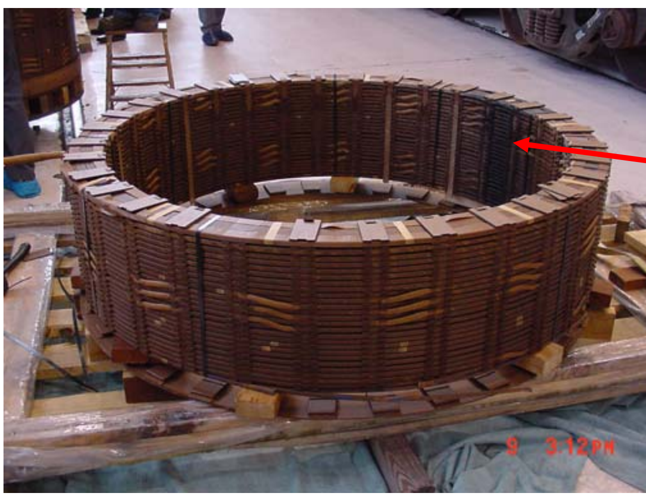
Besides tripping the circuit, there was no outward signs of transformer failure except for the Bucholtz relay. A visual inspection of the Bucholtz relay mounted on the transformer did indicate a major event occurred in that the relay was half filled with gas (Figure 3) which in service should be completely filled with oil.

Picture of Bucholtz Gas Relay (Found half filled with Gas)
FIGURE 3

INVESTIGATION AND TEARDOWN

After failure, the transformer was transported to a transformer repair facility where it was un-tanked. The failure investigation isolated the failure to one phase and the teardown of that phase began (Figure 4). The actual failure was isolated to disks 95 through 97 (starting from the bottom). This area represented the upper third of the winding, (see Figure 5). The failure consisted of a puncture that left a hole through the inner most portion of the disk (Figures 6 and 7).

Removal of Failed HV Winding
FIGURE 4



Area of Failure
FIGURE 5

Disks 95-97, Burnt Region
FIGURE 6

Hole in Disk 96
FIGURE 7

During the teardown investigation, a black or grayish coating was found on some of the copper, paper insulation and spacers. Scanning electron microscopy, energy dispersive X-ray (SEM/EDX) analysis showed this material to be copper sulfide.

LABORATORY ANALYSIS PERFORMED BY DOBLE

At the request of the transformer owner, Doble performed a variety of tests to assess the condition of the oil and paper insulation. Some of these tests included furanic compound analysis, phenol and cresol compound analysis, total sulfur content, elemental sulfur content, sulfur speciation, corrosive sulfur by ASTM D 1275 and a Doble modified corrosive sulfur method. The results of the testing are shown in the Tables 1 through 5.

TABLE 1
Results of the Furanic Compound, Phenol and Cresol Compound Analysis

Compound	Results
5-hydroxymethyl-2-furfural	<1 ug/L
furfuryl alcohol	<1 ug/L
2-furfural	4 ug/L
2-acetyl furan	<1 ug/L
5-methyl-2-furfural	<1 ug/L

Compound	Results
phenol	<10 ug/L
m-cresol	<10 ug/L
o-cresol	<10 ug/L
2,3-dimethyl phenol	<10 ug/L
2,6, dimethyl phenol	<10 ug/L
2,3,5-trimethyl phenol	<10 ug/L

TABLE 2
Results of the Various Sulfur Tests

Elemental Sulfur	Total Sulfur	Corrosive Sulfur ASMT D 1275	Doble Modified Corrosive Sulfur Test
<1 mg/kg	886 mg/kg	Non-corrosive	**Corrosive**

TABLE 3
Results of the Sulfur Speciation Test, ASTM D 5623

Compound	Result
hydrogen sulfide	<1 ppm
carbonyl sulfide	<1 ppm
methyl mercaptan	<1 ppm
ethyl mercaptan	<1 ppm
dimethyl sulfide	<1 ppm
carbon disulfide	<1 ppm
isopropyl mercaptan	<1 ppm
ethylene sulfide	<1 ppm
tert-butyl mercaptan	<1 ppm
n-propyl mercaptan	<1 ppm
ethyl methyl sulfide	<1 ppm
thiophene	<1 ppm
sec-butyl mercaptan	<1 ppm
isobutyl mercaptan	<1 ppm
ethyl sulfide	<1 ppm

Compound	Result
n-butyl mercaptan	<1 ppm
dimethyl disulfide	<1 ppm
2-methyl thiophene	<1 ppm
3-methyl thiophene	<1 ppm
tetra-hydro thiophene	<1 ppm
ethyl methyl disulfide	<1 ppm
2-methyl-tetra-hydro-thiophene	<1 ppm
2-ethyl thiophene	<1 ppm
2,5-dimethyl thiophene	<1 ppm
3-ethyl thiophene	<1 ppm
2,4 & 2,3-dimethly thiophene	<1 ppm
3,4-dimethyl thiophene	<1 ppm
methyl ethyl thiophenes	<1 ppm
trimethyl thiophenes	<1 ppm
tetramethyl thiophenes	<1 ppm

Compound	Result
benzothiophene	<1 ppm
methyl benzothiophenes	<1 ppm
dimethyl benzothiophenes	<1 ppm
trimethyl benzothiophenes	<1 ppm
tetra-methyl benzothiophenes	<1 ppm
dibenzothiophene	8 ppm
4-methyl dibenzothiophene	26 ppm
3-methyl DBZT + 2-methyl DBZT	42 ppm
1-methyl dibenzothiophene	31 ppm
4,6-dimethyl dibenzothiophene	27 ppm
dimethyl dibenzothiophenes	109 ppm
trimethyl dibenzothiophenes	88 ppm
tetra-methyl dibenzothiophenes	10 ppm
Unidentified volatile sulfur	545 ppm

TABLE 4
Results of the Total Metals Analysis, ASTM D 5185 (ppm = mg/kg)

Compound	Result	Compound	Result
Iron	<1 ppm	Titanium	<1 ppm
Chromium	<1 ppm	Silicon	14 ppm
Lead	2 ppm	Sodium	<1 ppm
Copper	<1 ppm	Magnesium	<1 ppm
Tin	<1 ppm	Calcium	<1 ppm
Aluminum	<1 ppm	Barium	<1 ppm
Nickel	<1 ppm	Phosphorous	<1 ppm
Silver	<1 ppm	Zinc	<1 ppm
Molybdenum	1 ppm	Vanadium	1 ppm

TABLE 5
Results of the Particulate Metals Analysis, Doble Test (ppb = ug/L)

Copper	Lead	Iron	Zinc	Aluminum	Silver
15 ug/L	<1 ug/L	<1 ug/L	2 ug/L	2 ug/L	<1 ug/L

In addition, several additional tests were performed on the paper insulation. One of these tests consisted of testing the copper content of the paper insulation. Paper samples were taken from individual conductor turns at different regions and depths along the failed high voltage winding as shown in Figure 8.

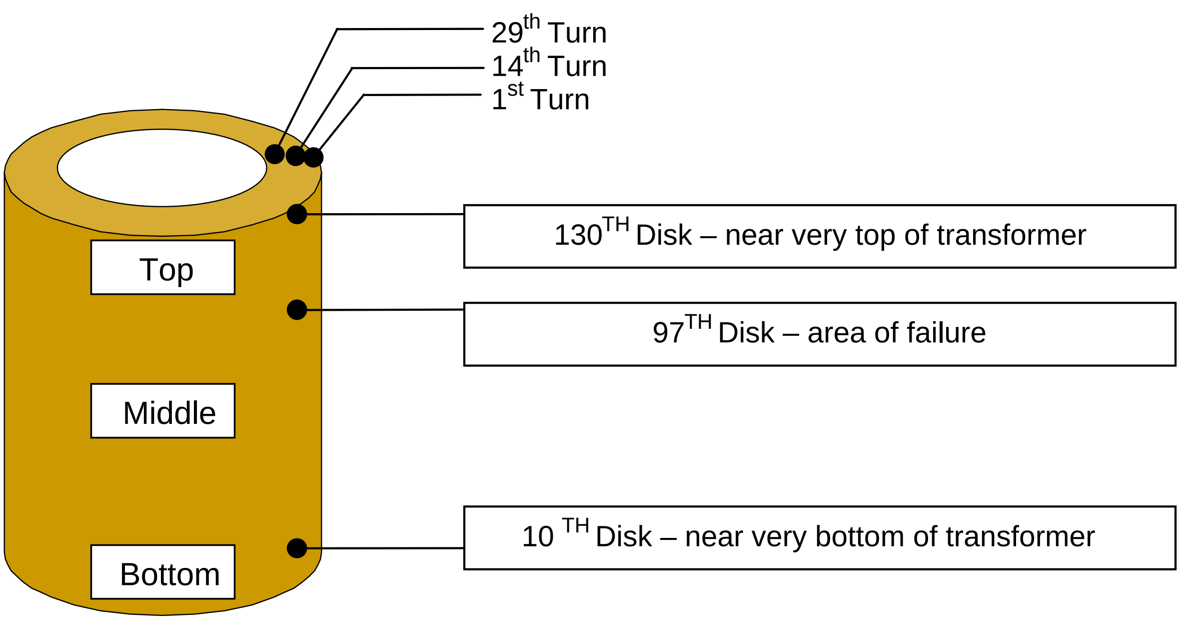
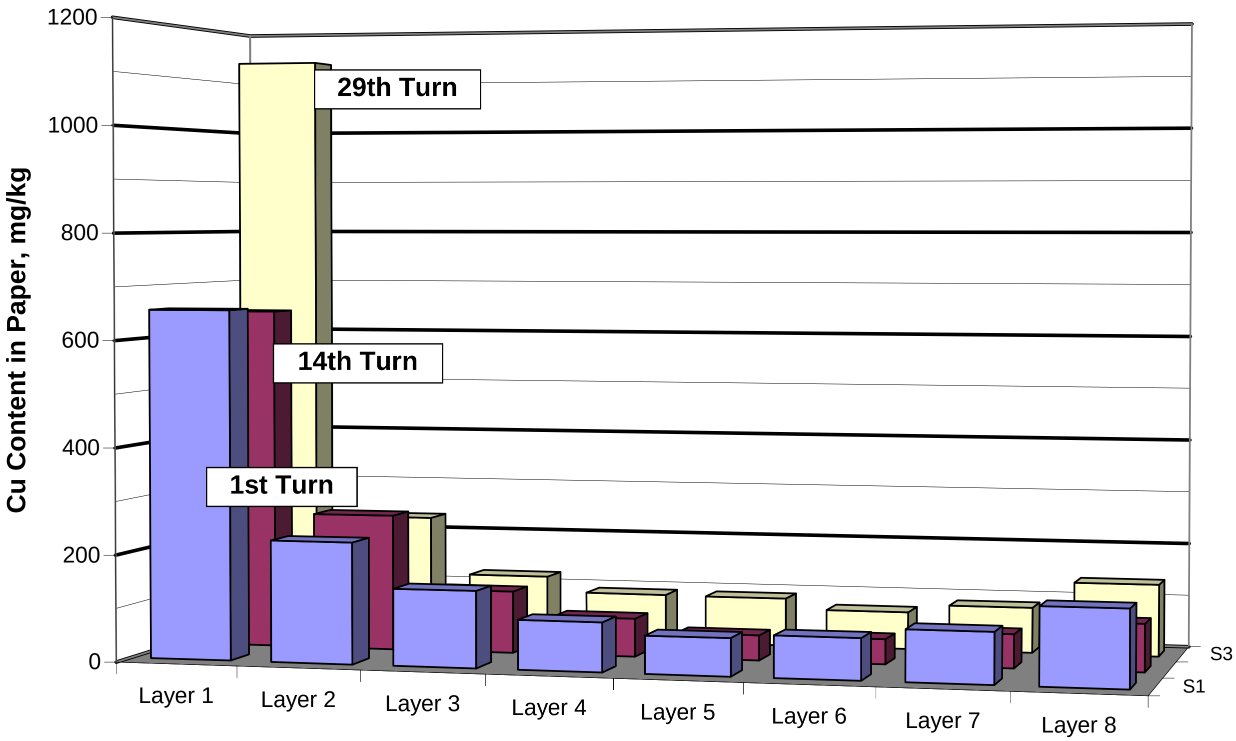


Diagram of Failed High Voltage Winding
FIGURE 8

Table 6 and Figure 9 catalogs the copper (Cu) concentration and illustrates its distribution throughout the paper layers of three turns on the 130th disk. This disk is located near the very top of the winding.

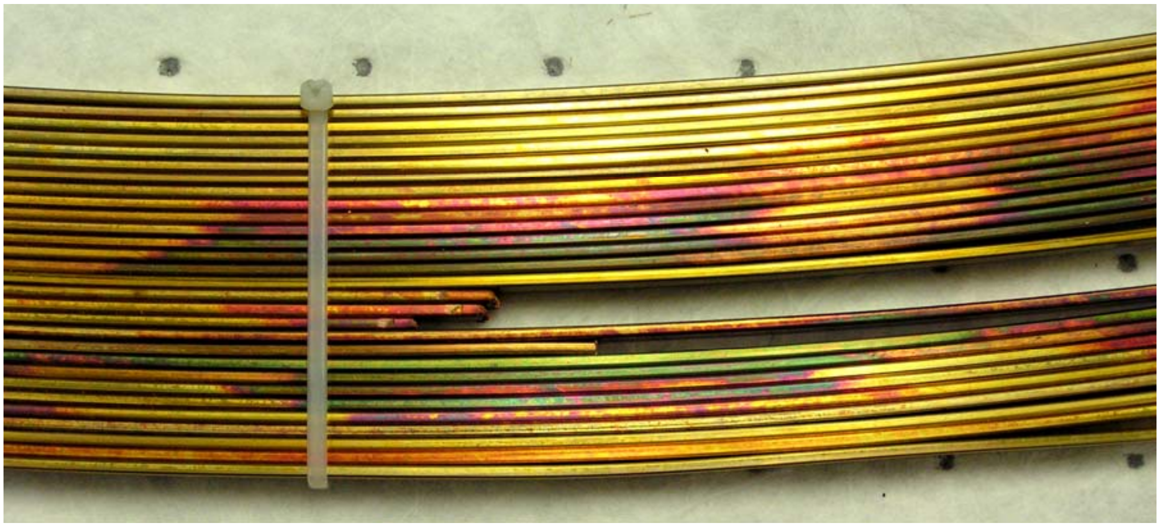
TABLE 6
Copper Concentration of Paper Layers in Winding Disk 130

Paper Layer	Turn 1 Cu Result, mg/kg	Turn 14 Cu Result, mg/kg	Turn 29 Cu Result, mg/kg
Layer 1, next to Conductor	656	647	1136
Layer 2	227	257	233
Layer 3	143	117	122
Layer 4	92	72	92
Layer 5	70	47	91
Layer 6	77	47	71
Layer 7	95	63	86
Layer 8	143	89	136



Distribution of Copper in Paper in Winding Disk 130
FIGURE 9

Removal of the paper insulation from the turn to perform the copper analysis on the paper also exposed the copper conductor. Significant discoloration of the copper was visible as shown in Figure 10. The copper turns in Figure 10 represent some of the 29 turns in Disk 130. This discoloration is different forms of copper-sulfur compounds.



Picture of Copper Turns in Disk 130
FIGURE 10

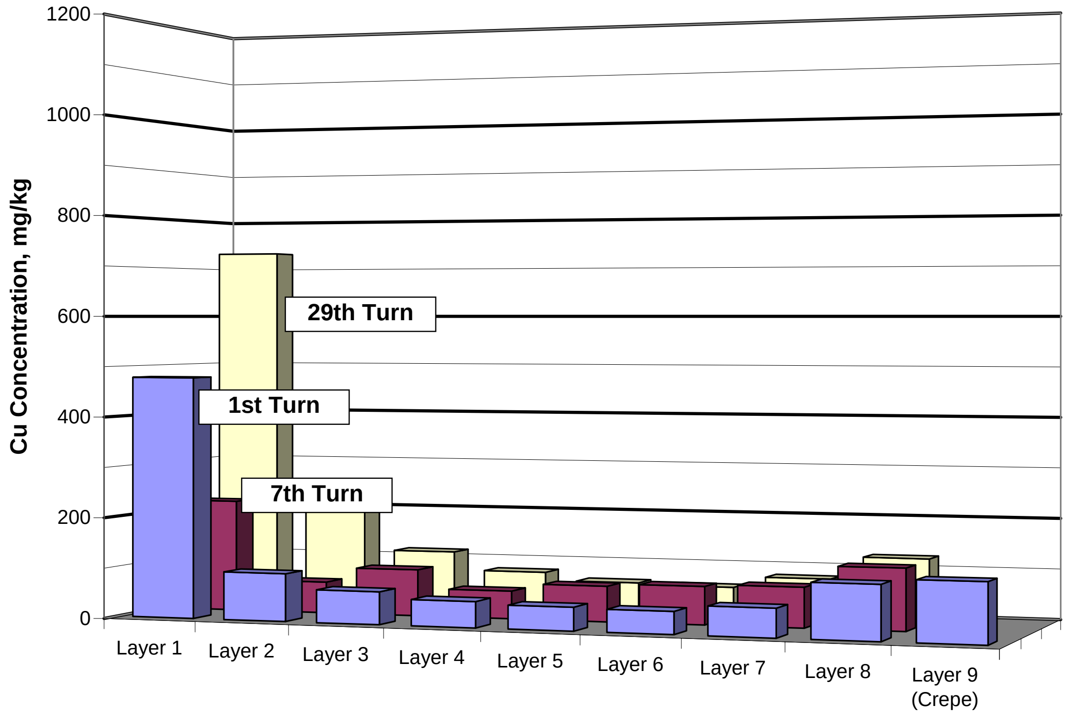
Removal of one piece of copper from this disk shows just how extensive some of the contamination really was. This is shown in Figure 11.

Picture of Copper Turn 11 in Disk 130
FIGURE 11

Table 7 and Figure 12 lists the copper (Cu) concentrations and shows its distribution throughout paper layers of three turns on the 97th disk. This disk was located in the direct vicinity of the failure. Figure 12 has been depicted on the same concentration scale as Figure 9 for comparison.

TABLE 7
Copper Concentration of Paper Layers in Winding Disk 97

Paper Layer	Turn 1 Cu Result, mg/kg	Turn 7 Cu Result, mg/kg	Turn 29 Cu Result, mg/kg
Layer 1, next to Conductor	478	222	731
Layer 2	94	62	215
Layer 3	64	92	114
Layer 4	51	55	77
Layer 5	46	70	61
Layer 6	44	75	57
Layer 7	56	79	79
Layer 8, some of it exposed as outermost	106	121	124
Layer 9, CREPE, outermost layer facing oil	116		

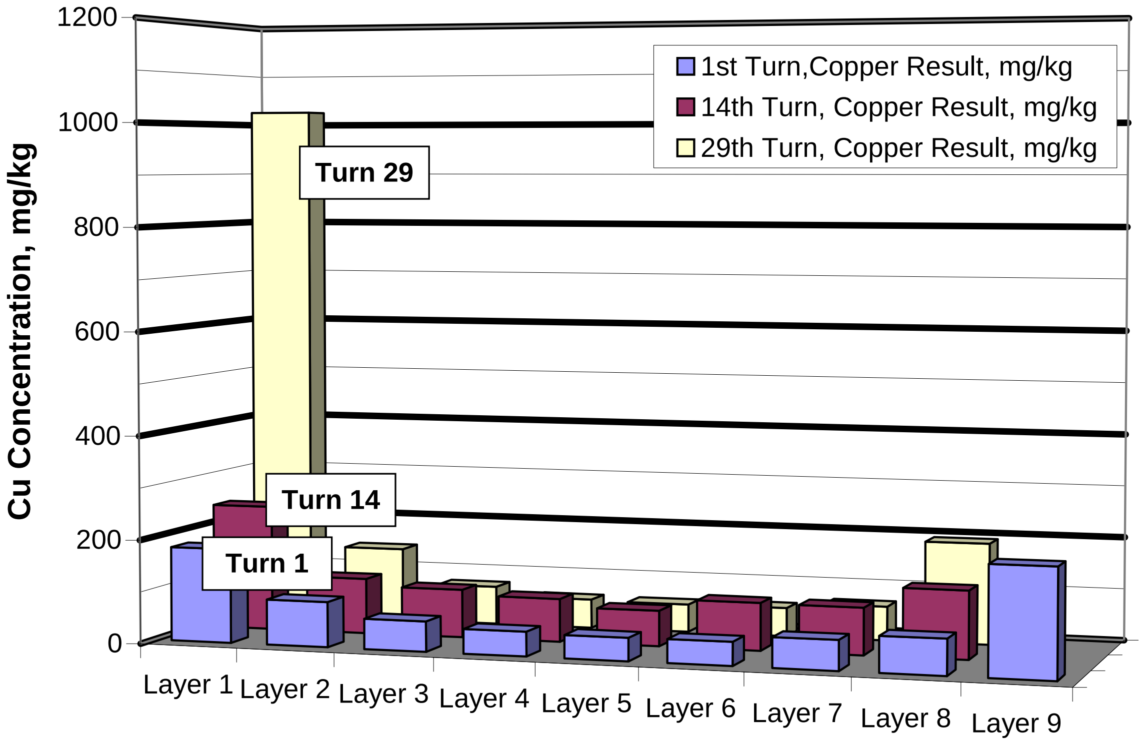


Distribution of Copper in Paper in Winding Disk 97
FIGURE 12

Table 8 and Figure 13 catalogs the copper (Cu) concentrations and illustrates the distribution throughout the paper layers of the three winding turns on the 10th disk. This disk was located close to the bottom of the transformer. Figure 13 depicts the same concentration scale as Figure 9 for comparison.

TABLE 8
Copper Concentration of Paper Layers in Winding Disk 10

Paper Layer	Turn 1 Cu Result, mg/kg	Turn 14 Cu Result, mg/kg	Turn 29 Cu Result, mg/kg
Layer 1, next to Conductor	181	243	1024
Layer 2	87	107	143
Layer 3	58	93	74
Layer 4	47	83	56
Layer 5	44	68	54
Layer 6	45	91	55
Layer 7	57	90	66
Layer 8	68	130	195
Layer 9, Crepe	206		



Distribution of Copper in Paper in Winding Disk 10
FIGURE 13

DISCUSSION OF LABORATORY RESULTS

The results of the furanic, phenol and cresol compounds do not indicate any advance or abnormal aging of the cellulosic insulation. Even though there was a clear indication of failure (Figure 7), the amount of material involved in the failure was very small and would not have increased the byproduct concentration significantly.

The tests for total sulfur, elemental sulfur and corrosive sulfur by ASTM Method D 1275 also indicated that the oil was satisfactory for use. However, Doble employs a modified corrosive sulfur test which is more severe than the ASTM test and in this analysis the oil was found to be clearly corrosive.

ASTM Method D 5623 was also utilized. In this test certain sulfur species are identified and quantified by gas chromatography using a sulfur selective detector. Sulfur is present in crude oils used to make transformer oil. The refinery attempts to remove or convert the harmful sulfur species so a corrosive condition does not occur during use in service. Some sulfur compounds such as thiophenes can actually aid in the oxidation stability of the transformer oil and may also act as metal passivators/deactivators reducing the catalytic effect on oil oxidation in transformers [1]. This analysis showed that although there were numerous thiophenes present, there was a large amount of unidentified volatile sulfur compounds also present (Table 3) which may have contributed to the corrosive condition that was found.

The different types of metal analyses performed indicated the presence of a small amount of particulate copper and a considerable concentration of dissolved silicon. The low concentration of copper would not normally be of concern. It may indicate that the oil was involved in the transportation of copper ions throughout the transformer but it was probably a minor influence. Because the concentration of silicon was so elevated the analysis was repeated to confirm the concentration. In addition a foaming tendency test was performed. The results from this test suggest that the fluid is contaminated with a silicone liquid or some other silicone based product. Although, part of the initial laboratory investigation, the presence of silicon and silicone probably did not contribute to the failure of the transformer.

The copper analysis on the paper insulation was a clear indication that copper was being transported from the conductor to the layers of paper surrounding the conductor with the highest concentration being found next to the conductor. Of even more interest is the distribution of copper in the layers. The copper concentration followed a distorted U-shaped curve from inside to outside with the lowest concentration being in the middle layers of paper wrapped around the conductor. This illustrates that paper is adsorbing copper not only from the conductor on the inside layers but from the bulk oil on the outside layers so it is being impacted from both directions. It also shows that copper ions are being transported through numerous layers of paper. In previous experiments performed at Doble, new paper received from the paper manufacturer only contained about 1 to 3 mg/kg (ppm) of copper in the paper.

What is also shown in these results is that the inner most turn (Turn 29), exhibits the highest concentration of copper of all the turns in a disk and it may be due to the oil flow that exists between the low voltage and high voltage windings. Even in one of the bottom most disks (Disk 10), though the overall copper concentration was much less then the other two disks tested, the 1st layer of the 29th turn still exhibited a very high copper concentration. Another interesting fact is that the copper concentration in the paper also increases as the disk position increases in the winding. Basically, the top of the winding exhibited the highest overall copper concentration even though this was not the immediate area in which the failure occurred. As this was a core form transformer, it is thought that the copper distribution in other core form units or designs would be similar if a problem of this type should exist. Figure 14 provides an overall diagrammatic view of the transported copper distribution determined in this analysis.

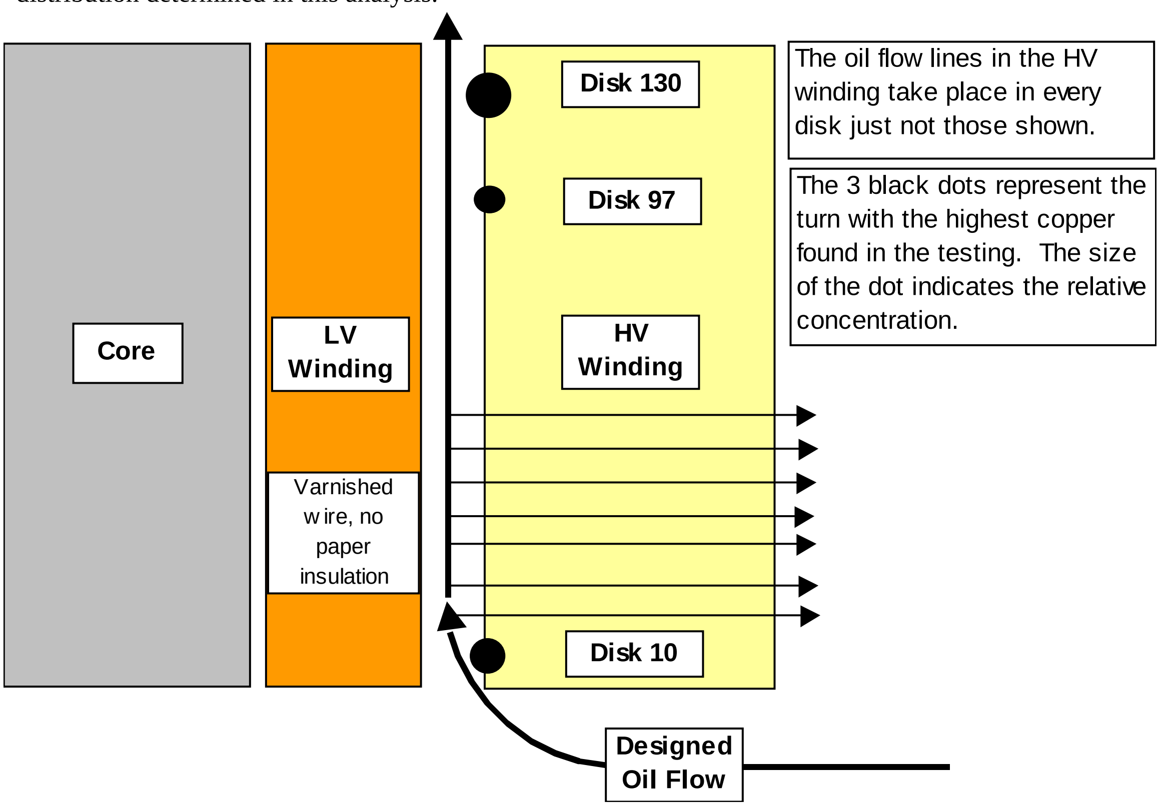


Diagram of GSU Transformer Winding
FIGURE 14

CONCLUSIONS

This paper discussed some of the details of the teardown and laboratory investigation of a failed GSU transformer. Teardown evidence and laboratory analysis showed that the failure was in part the result of copper and copper sulfide contamination of the insulating paper of the windings that led to a reduction in dielectric strength. Several analytical test techniques were used to make clear the reason for the failure and to understand the dynamics of the contamination. Testing for the copper concentration in the paper of the high voltage winding provided important information on the transport and distribution of copper as result of the corrosive sulfur condition and showed how the conductor and oil flow influenced the copper concentration in the transformer.

REFERENCES

[1] Lewand, Lance R. "The Role of Corrosive Sulfur in Transformers and Transformer Oil", *Proceedings of the Sixty-Ninth Annual International Conference of Doble Clients*, Insulating Materials Session, 2002.

AUTHOR BIOGRAPHY

Lance Lewand is the Laboratory Manager for the Doble Materials Laboratory and is also the Product Manager for the Doble ***DOMINO***, a moisture-in-oil sensor. The Materials Laboratory is responsible for routine and investigative analyses of liquid and solid dielectrics for electric apparatus. Since joining Doble in 1992, Mr. Lewand has published numerous technical papers pertaining to testing and sampling of electrical insulating materials and laboratory diagnostics.

Mr. Lewand was formerly Manager of Transformer Fluid Test Laboratory and PCB and Oil Field Services at MET Electrical Testing Company in Baltimore, MD for seven years. His years of field service experience in this capacity provide a unique perspective, coupling laboratory analysis and field service work.

Mr. Lewand received his bachelor of science degree from St. Mary's College of Maryland. He is actively involved in professional organizations such as ASTM D-27 since 1989 and is a sub-committee chair. He is also the secretary of the Doble Committee on Insulating Materials.