Q. As noted at page 1, lines 11-13, of Hydro's Report on the Replacement of Equipment Resulting from Sunnyside T1 Transformer Failure:

"On January 4, 2014 Sunnyside T1 transformer faulted, with the most probable cause being a bushing failure that initiated inside the transformer. As a result of this fault, a fire developed leading to the irreparable damage of the transformer and associated equipment."

i) Has Hydro determined the cause of the "bushing failure"? If so, please provide any reports, analysis or other documentation in which the cause of such "bushing failure" is considered or analysed.

ii) If the cause or the "bushing failure" has not yet been determined, will Hydro attempt to determine the cause of the "bushing failure" in the future?

iii) Are such bushings inspected/maintained regularly? If yes, please provide details of the inspections/maintenance carried out on the subject bushing, including any documentation/reports related to such inspection/maintenance.

iv) Is it possible that the cause of the "bushing failure" was lack of inspection and/or maintenance of the bushing by Hydro?

A. i) Hydro has not determined the cause of the bushing failure. The transformer Original Equipment Manufacturer (OEM), who investigated the cause of the failure on behalf of Hydro, was unable to identify a cause with certainty and could only indicate in its final report that: *"Based on the internal inspection observations, all the information available and the system analysis findings, it is concluded that most probably the LV1 or LV2 bushing failed first which initiated the failure and resulting fire."* See IC-NLH-1 Attachment 1 page 57. The explosion and/or fire resulting from the failure destroyed the physical evidence that would have revealed the cause.

ii) As indicated in part i) of this response, due to the physical evidence being destroyed, Hydro will not be able to determine the cause of the bushing failure in the future.

iii) Bushings are inspected/maintained regularly as a part of Hydro's terminal station visual inspections and Hydro's transformer maintenance programs. The latest visual inspection of the bushings for Sunnyside Transformer T1 was completed in October 2013 (See IC-NLH-1 Attachment 2 for the completed form) and no bushing concerns were noted. The data from the 2007 transformer maintenance on Sunnyside Transformer T1, specifically the power factor testing of the bushings, were reviewed during the Root Cause Investigation of System Disturbances Analysis which was filed with the Board as a part of the March 24, 2014 Hydro Interim Report - *Review of Supply Disruptions and Rotating Outages* - Volume II. These results are also contained in IC-NLH-1 Attachment 1, pages 33 and 34. The Root Cause Investigation of System Disturbances Analysis completed an overall review of the events leading up to the January 2-8, 2014 power system disturbances, and included the fire at Sunnyside Transformer T1 with a review of the maintenance data associated with this transformer and its bushings.

iv) The "*Root Cause Investigation of System Disturbances on January 4 and 5, 2014*" (filed with the Board on March 24, 2014 as Schedule 8 of the Hydro Interim Report under the *Investigation and Hearing into Supply Issues and Power Outages on the Island Interconnected System*) did not identify the lack of inspection and/or maintenance of the bushings as a cause of the failure, hence Hydro does not believe that this is a cause of the failure.

DESIGN STUDY AND FAILURE INVESTIGATION FOR AUTO TRANSFORMER

NALCOR

SERIAL # 289147

CANADIAN GENERAL ELECTRIC

PREPARED BY

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ABB Project Number: 560246

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April 23, 2014; Rev0

Executive Summary

A comprehensive short circuit and dielectric study of the design was performed for transformer SN 289147 that was manufactured in 1978 and failed in service in 2014. A review of maintenance data and DGA history was completed. A failure investigation and inspection was also performed.

The short circuit design study showed that the HV and LV windings are able to withstand short circuit forces while the TV winding end rings are not strong enough to withstand the short circuit forces.

The Dielectric study showed that all windings and cable clearances are within the acceptable design levels for the voltage stresses in this transformer.

The DGA, oil quality, transformer power factor and maintenance history of the four transformers were reviewed.

For SSD T1 – CGE 288147

The DGA results showed that:

- The concentration of Acetylene (C_2H_2) has been above IEEE C57.104-2008 guide condition level 1 (2 ppm) since 1991, The level went up and down since then but was almost stable around the 10ppm. This could be oil leaking from the LTC diverter compartment.
- The oil samples from this transformer have consistently shown high oxygen concentrations.

The oil physical results showed that: (Main tank)

- The interfacial tension values are around 28.0 dynes/cm2 which are below the 32 dynes/cm2 limit recommended by IEEE C57.106-2002 for ≥ 230kV transformers.

The oil physical results showed that: (LTC tank)

- The measured breakdown voltage (around 22.0 kV/mm for LTC-A,B,C) is below the minimum requirement (28 kV/mm for 1 mm gap and 45 kV/mm for 2 mm gap) as outlined by IEEE C57.106-2002.
- The oil samples taken from the LTC-A tank does show moisture content of more than 25 ppm.

The power factor measurements showed that:

- The winding power factor values (CH & CT) are below 0.5%.
- The C1 power factor and capacitance values for HV & LV bushings are all acceptable.
- The measured C2 capacitance for HV & LV bushings is higher than the nameplate values by more than 10%.
- The hot collar tests for TV bushings and neutral bushing are below recommended limit.
- The Doble exciting current test are normal.

The maintenance history showed that:

- The winding resistance test for HV winding is consistent between phases, however the measured resistance is much lower than the other sister units.
- The winding resistance tests for LV & TV windings are consistent between phases, and also very close to the other sister units.
- The insulation resistance test was performed and results look normal in G-ohms, however the polarization index is lower than the ABB suggested value of 2.0 for HV/LV to ground.

For SSD T4 – CGE 288838

The DGA results showed that:

- The concentration of Acetylene (C2H2) has been above IEEE C57.104-2008 guide condition level 1 (2 ppm) since 1991, The level went up and down since then but was almost stable around the 5ppm. This could be oil leaking from the LTC diverter compartment.
- The oil samples from this transformer have consistently shown high oxygen concentrations.

The oil physical results showed that: (Main tank)

- The latest measured breakdown voltage (52.0kV/mm) is above the minimum requirement (30kV/mm) as outlined by Doble Engineering for 230kV transformers.
- The interfacial tension values are around 33.6 dynes/cm2 which is slightly above the 32 dynes/cm2 limit recommended by IEEE C57.106-2002 for 230kV transformers. Lower values may indicate oil soluble contaminants and oxidation products in oil.
- The measured Acid Numbers for the oil samples are all below the recommended limits.
- The measured power factor values at 25/100°C are all below the suggested limits.
- The moisture in oil is within the acceptable limits.

The oil physical results showed that: (LTC tank)

- The measured breakdown voltage (between 20.0 kV/mm and 21.0 kV/mm for LTC-A,B,C) is below the minimum requirement (28 kV/mm for 1 mm gap and 45 kV/mm for 2 mm gap).
- IEEE C57.106-2002 Table 12 recommends that the maximum limit of water content in oil for LTC is not to exceed 25 ppm. The oil samples taken from the LTC tank show moisture content much less than 25 ppm.

The power factor measurements showed that:

- The winding power factor value CH is below the allowed limit, but CT is above 0.5%.
- The C1 power factor and capacitance values for HV & LV bushings are all acceptable.
- The measured C2 capacitance for HV & LV bushings is higher than the nameplate values. This needs to be compared to initial benchmark test results.
- The hot collar tests for TV bushings and neutral bushing are below recommended limit.
- The Doble exciting current test are normal.

The maintenance history showed that:

- The winding resistance test for HV & LV & TV windings is consistent between phases.
- The ratio test was not performed.
- The core Megger test was performed and result looks normal.
- The insulation resistance test was performed and results look normal in G-ohms however the polarization index is lower than the ABB suggested value of 2.0.

For STB T1 – CGE 288894

The DGA results showed that:

- The concentration of Acetylene (C2H2) has been below IEEE C57.104-2008 guide condition level 1 (2 ppm) since 2009. However the DGA sample for the year 1979 shows high level of C2H2. This could be a bad oil sample.
- The oil samples from this transformer have consistently shown high oxygen concentrations.

The oil physical results showed that: (Main tank)

- The latest measured breakdown voltage (62.0kV/mm) is above the minimum requirement (50kV/mm) as outlined in IEEE C57.106-2002 for 230kV transformers with service aged insulating oil based on D1816-2mm method.

- The interfacial tension values are around 30.4 dynes/cm2 which is below the suggested limits (32 dynes/cm2) recommended by IEEE C57.106-2002 for 230kV transformers. Lower values may indicate oil soluble contaminants and oxidation products in oil.
- The measured Acid Numbers for the oil samples are all below the recommended limits.
- The measured power factor values at 25/100°C are all below the suggested limits.
- The moisture in oil is within the acceptable limits.

The oil physical results showed that: (LTC tank)

- The latest measured breakdown voltage is 30, 31 and 33 kV/mm for LTC-A,B,C. the suggested limits is 28 kV/mm for 1 mm gap and 45 kV/mm for 2 mm gap as outlined by IEEE C57.106-2002.
- IEEE C57.106-2002 Table 12 recommends that the maximum limit of water content in oil for LTC is not to exceed 25 ppm. The latest oil samples taken from the LTC tank show moisture content of less than 25 ppm.

The power factor measurements showed that:

- The winding power factor value CH & CT are below the allowed limit.
- The C1 power factor and capacitance values for HV & LV bushings are all acceptable.
- The measured C2 capacitance for HV & LV bushings is higher than the nameplate values. This needs to be compared to initial benchmark test results.
- The hot collar tests for TV bushings and neutral bushing are below recommended limit
- The Doble exciting current test are normal.

The maintenance history showed that:

- The winding resistance test for HV & LV windings is consistent between phases.
- The deviation of the TV winding resistance between phases is 20%.
- The ratio test was not performed.
- The core Megger test was performed and result looks normal.
- The insulation resistance test was performed and results look normal in G-ohms however the polarization index is lower than the ABB suggested value of 2.0 for HV to ground.

For STB T2 – CGE 288839

The DGA results showed that:

- The transformer has consistently shown very high concentrations (>20 ppm) of Acetylene (C2H2) since 1986, which is far above the IEEE C57.104-2008 guide condition level 1 (2 ppm). The high concentration of C2H2 indicates that possible high energy arcing occurred somewhere inside the transformer. The other reason could be oil leaking from the LTC diverter compartment. The Acetylene levels are about 10ppm for few years now. This needs to be monitored closely. Any sudden increase of Acetylene needs to be investigated.
- The oil samples from this transformer have consistently shown high oxygen concentrations

The oil physical results showed that: (Main tank)

- The latest measured breakdown voltage (68.0kV/mm) is above the minimum requirement (50kV/mm) as outlined in IEEE C57.106-2002 for 230kV transformers with service aged insulating oil based on D1816-2mm method.
- The interfacial tension values are around 28.7 dynes/cm2 which is below the suggested limits (32 dynes/cm2) recommended by IEEE C57.106-2002 for 230kV transformers.
- The measured Acid Numbers for the oil samples are all below the recommended.
- The measured power factor values at 25/100°C are all below the suggested limits.
- The moisture in oil is within the acceptable limit.

The oil physical results showed that: (LTC tank)

- The latest measured breakdown voltage is 17, 21 and 23 kV/mm for LTC-A,B,C, which is below the suggested minimum limits (28 kV/mm for 1 mm gap and 45 kV/mm for 2 mm gap).
- IEEE C57.106-2002 Table 12 recommends that the maximum limit of water content in oil for LTC is not to exceed 25 ppm. The latest oil samples taken from the LTC tank show moisture content of more than 25 ppm for all three LTCs.

The power factor measurements showed that:

- The winding power factor value CH & CT are below the allowed limit.
- The C1 power factor and capacitance values for HV & LV bushings are all acceptable.
- The measured C2 capacitance for HV bushings is higher than the nameplate values by more than 10%. <u>This needs to be compared to initial benchmark test results and investigated.</u> The measured C2 capacitance for LV bushings is higher than the nameplate values but within 10%.
- The hot collar tests for TV bushings and neutral bushing are below recommended limit.
- The Doble exciting current test are normal.

The failure inspection of SSD T1 showed the following:

- All transformer bushings are damaged.
- The tap changer diverter cylinders of Phases 1 and 3 were separated from their aluminum flanges at the cover.
- There was no indication that the fault originated in the tap changers compartment.
- No signs of flash over were seen in the cleats and leads including tap leads.
- All windings looked good with no signs of failure within the windings. It was not possible however to see the internal windings.
- No sign of phase to phase failure in the windings was found during the inspection.
- The L1 & L3 bushing's porcelain inside the transformer were shattered. Also marks of flashover were seen on core clamp just opposite to Phase 1 LV bushing.
- For Phases 1 and 2 the leads connecting the LV bushings to the windings are disconnected. It seems the two leads were mechanically pulled and cut at the crimp during the fault when the cover opened up. The insulation of the leads looks intact with no signs of failure.
- Spitting and melting copper were seen on the LV windings conductor copper strands of phase one.

The system analysis during the fault showed that:

- Between 9:03:21 and 9:04:49 something happened causing the MVAR difference between T1 & T4. Most probably T1 transformer was providing (compensating) the MVAR while there was a fault in T4.
- There is no indication that a system disturbance caused the failure.
- There is no indication that the failure was initiated externally.
- There is no indication that there was a phase to phase failure.

Based on the internal inspection observations, all the information available and the system analysis findings, it is concluded that most probably the LV1 or LV2 bushing failed first which initiated the failure and resulting fire.

The following is recommended during dismantling/scraping of the failed unit:

- Inspect closely the LTC diverter switches.
- As there was lots of carbon, debris, oil and water inside the tank during the internal inspection, closer inspection of the windings after un-tanking the active part is recommended.

The following is recommended for the other three transformers:

- Comprehensive DGA, oil quality tests and transformer testing is to be planned.
- Any bushings with high C2 capacitance need to be compared to initial benchmark test results. Higher results need to be investigated.
- As the bushings of these transformers are about forty years old, it is recommended to replace the bushings.
- Add a conservator diaphragm.
- Consider adding oxidation inhibitor to oil.
- Monitor Acetylene (C_2H_2) closely especially for (STB T2).
- Confirm that the cause of the acetylene is due to seeping from the LTC diverter oil compartment. This can be done by applying pressure on the diverter compartment and checking if oil leaks into the main compartment (the pressure drops).
- Consider adding online gas monitor.
- Consider adding bushing monitors.
- Measure the oil break down voltage per ASTM D1816 (1mm or 2mm) method.
- Repeat the TV windings resistance test (on unit STB T1) and compare to the sister unit results.
- Repeat the HV resistance test (on unit SSD T1) and compare to the sister unit results.
- Inspect and overhaul the LTC diverters. Most LTC manufacturers recommend LTC diverter inspections every 7 years. It is also recommended to re-condition or replace the oil in the LTC diverter tanks with new oil if it is not already done.

Table of Contents

1. Introduction

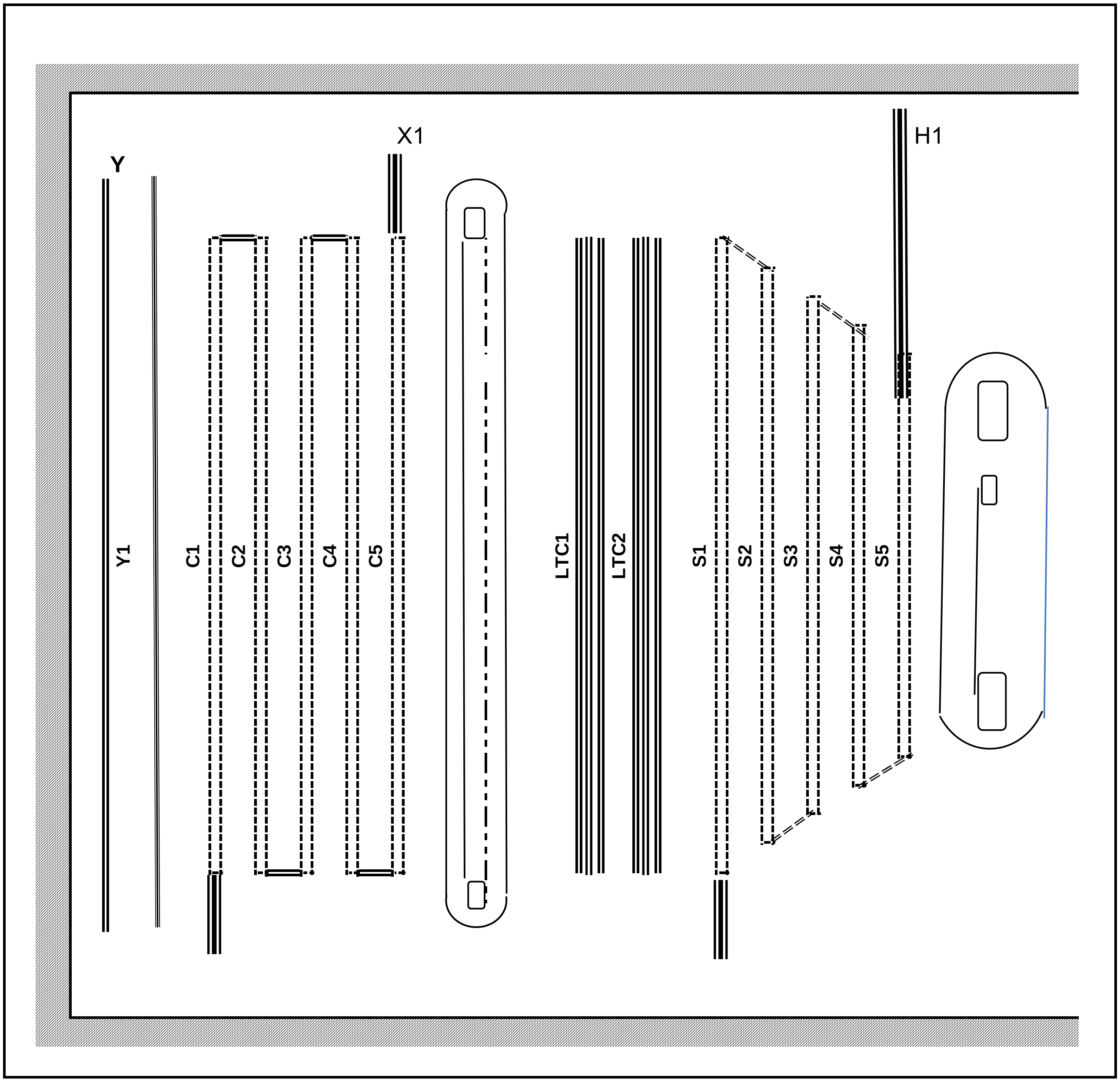
This transformer, SN 289147, failed and caught fire on January 4, 2014. The information available shows that the fault took more cycles than normal to be cleared. The transformer was on fire for about 66 hours. The transformer sustained major damage due to the failure and the fire. The customer requested that ABB inspect the transformer to try and identify the cause of the failure.

A comprehensive short circuit and dielectric study of the design is also performed. There are four transformers manufactured to the same design. These transformers are built by Canadian General Electric under the Serial Numbers 288838, 288839 & 288894 in 1976 and 289147 in 1978.

Table 1 – Auto Transformer

Identification	Canadian General Electric
Rating	75/100/125 MVA, ONAN/ONAF/ONAF, 65°C Rise, 3Ph, 60Hz
Voltage	HV: 230 kV Grd Y, +5, -15 % ON Load taps LV: 138 KV Grd Y. TV: 6.9 KV Delta.
Lightning Insulation Levels	HV: 900 kV BIL LV: 550 kV BIL HV Neut: 110 kV Bil TV: 95 kV BIL
Core	3 phase unit, 3 legged design.
Windings	On each leg from the core outward: TV: Single layer, copper, MTC conductors. Shield LV : 5 Layers, copper, MTC conductors. Shield RV: 2 layers. Each with 4 multi starts, copper, MTC conductors. HV : 5 Layers, copper, MTC conductors. Shield.
Cooling Equipment	5 Radiators (156 tubes each) 9 Fans with 28" diameter
Manufacturing Date	First three units were built in 1976 Fourth unit was built in1978 All units built in Guelph, Ontario.

Figure 1 - Schematic Diagram of the Windings



2. Short Circuit Study

A 3D FEM leakage flux program was used to model this design. This program calculates the flux pattern in the windings as well as the short circuit currents in each winding and the associated forces.

2.1. Procedure

System Impedance:
From the original design, the system available MV is 3000 MVA on 230 KV side and 2000 MVA on the 138 kV side. This will translate into a 4.167% Impedance on the 230 kV side and 6.25% impedance on the 138 kV side on the 125 MVA base. These values are used in the analyses.

Short Circuit Calculation:
The transformer short circuit forces were analyzed with the on load tap changer on rated, maximum and minimum tap positions.

The transformer core and windings were modeled on a computer program to enable the magnetic field and force calculations to be calculated. This program calculates the winding impedances between pairs of winding and uses the system impedances to calculate the short circuit currents in the transformer windings at the different tap positions. The program then calculates the axial and radial forces on each winding. In this case the forces are calculated on each layer of each winding with more than one layer.

These forces are than used in the design program. From the characteristics of the windings and the type of conductors used, the effect of the forces is derived and the allowable limits are calculated.

2.2. Windings Short Circuit Capability

From the program results, the forces were calculated and compared with the allowed limits.

Table 2 - Short Circuit Calculations for the TV Winding (single Layer)

TV Winding (Single Layer)		Calculated	Allowed
Average radial inward stress	Psi	19 278	39 347
Dynamic conductor tilting stress	Psi	11249	12000
Axial pressure on end rings	Psi	**10500**	6000

Note:

This winding is failing on axial forces. The winding pressboard end rings are not strong enough to sustain the axial force. The calculated force is higher than the strength of the end ring material.

The other stresses on this winding are within the limits of the design.

Table 3 - Short Circuit Calculations for the Common Winding (Five Layers)

Common Winding (Five Layers)		Calculated	Allowed
Average radial inward stress	Psi	2899	24183
Dynamic conductor tilting stress	Psi	3779	12000
Axial pressure on end rings	Psi	5750	6000

Note:

This winding is adequately designed for the short forces for all the criteria that needed to be checked.

Table 4 - Short Circuit Calculations for the Tap Winding

Tap Winding (Two Layers)		Calculated	Allowed
Average radial inward stress	Psi	5805	22489
Dynamic conductor tilting stress	Psi	1432	12000
Axial pressure on end rings	Psi	3000	6000

Note:

This winding is adequately designed for the short forces for all the criteria that needed to be checked.

Table 5 - Short Circuit Calculations for the Series Winding (Five Layers)

Series Winding (Five Layers)		Calculated	Allowed
Average radial outward stress	Psi	11327	40000
Dynamic conductor tilting stress	Psi	1763	2484
Axial pressure on end rings	Psi	4000	6 000

Note:

This winding is adequately designed for the short forces for all the criteria that needed to be checked.

3. Dielectric Study

The following is an insulation study of the transformer using ABB designs tools and standards.

3.1. Procedure

The design information was obtained from the archives and the transformer insulation clearances were checked against ABB standards.

For the purpose of the study, it was assumed that the quality of the transformer oil and insulation was acceptable for doing full level insulation testing as if the transformer was new.

3.2. Major Winding insulation

Below in Table 6 and Table 7 are shown actual and allowed calculated electrical clearance values for the major winding insulation. The calculation shows that the insulation arrangement is satisfactory.

Table 6 – Radial Clearances

		Actual	Minimum
Core Leg - TV Winding	mm	9	9
TV Winding - Ground Shield	mm	11	8
Ground Shield - Common Winding	mm	10	10
Common Winding - Tap Winding	mm	11	11
Tap Winding – Series Winding	mm	28	17
Phase – Phase	mm	189	88

Table 7 – Axial Clearances

		Actual	Minimum
TV Winding – Core Yokes	mm	157	33
Common Winding - Core Yokes	mm	152	121
Tap Winding – Core Yokes	mm	152	121
Series Winding – Core Yokes	mm	233	204

All Winding leads, including tap leads, clearances to each other and to ground are within the design allowed rules.

4. Dissolved Gas in Oil Analysis (DGA)

4.1. SSD T1 - (CGE 289147)

Below is the report of the DGA data for the period of 1991 to 2013. The gas signatures for this transformer are shown in **Figure 2** to **Figure 4**.

The following is noted for the transformer DGA:

- The concentration of Hydrogen (H2) has been well below IEEE C57.104-2008 guide condition level 1 since 1991, the highest level was 49 ppm.
- The concentration of Methane (CH4) and Ethane (C2H6) have been steadily low for the period of the data provided. The Ethylene (C2H4) level is slightly above condition level one of the IEEE C57.104-2008 guide since 1991.
- The concentration of Acetylene (C2H2) has been above IEEE C57.104-2008 guide condition level 2 since 1991. The level went up and down since then but was almost stable around the 10ppm. This could be oil leaking from LTC diverter compartment.
- The carbon dioxide level has been below the IEEE C57.104-2008 guide condition level 2 for the time period provided. The carbon monoxide level is slightly above the IEEE C57.104-2008 guide condition level 1 since 1991. However the ratio of CO2/CO is between 4 and 9. The

normal $CO2/CO$ ratios are typically in the range of 5-9. The ratio of the carbon oxides suggests that the concentrations are due to the normal aging process of the transformer.

- Shown below in **Figure 5** is a distribution plot of carbon oxide gas levels taken from a survey by the IEEE Transformer Committee using > 520,000 data records of units in service. This very large quantity of data is being used to revise the gas level limits in C57.104 (the famous Table 1 with condition 1 – 4 levels) – note that the levels will be increased. As can be seen, the 90^{th} percentile levels are 700 ppm and 7500 for CO and CO2 respectively. **Figure 6** shows the CO distribution by age categories and for 30 – 40 years category, the 90^{th} percentile is about 700 ppm. The history gassing on this transformer was around 500 ppm and 3600 ppm for CO and CO2 respectively. Thus these levels are well below the 90^{th} percentile of the IEEE data for the age of this unit.
- The presence of large concentrations of oxygen in the oil can promote the formation of acids in the oil and cellulose and accelerate the aging rate of the cellulose insulation. It is recommended that the concentration of oxygen in the transformer be less than 2000 ppm (Refer to CIGRE report 323 – Aging of Cellulose in Mineral-Oil Insulated Transformers). The transformer maintenance record (09/21/2007) provided by the customer does not mention if the oil had ever been vacuum processed since 1991. The oil samples from this transformer have consistently shown very high oxygen concentrations (>20,000 ppm). The source of this high oxygen is the free-breathing oil conservator. To reduce the oxygen in the transformer oil and eliminate the uncertainty concerning the gas generation.

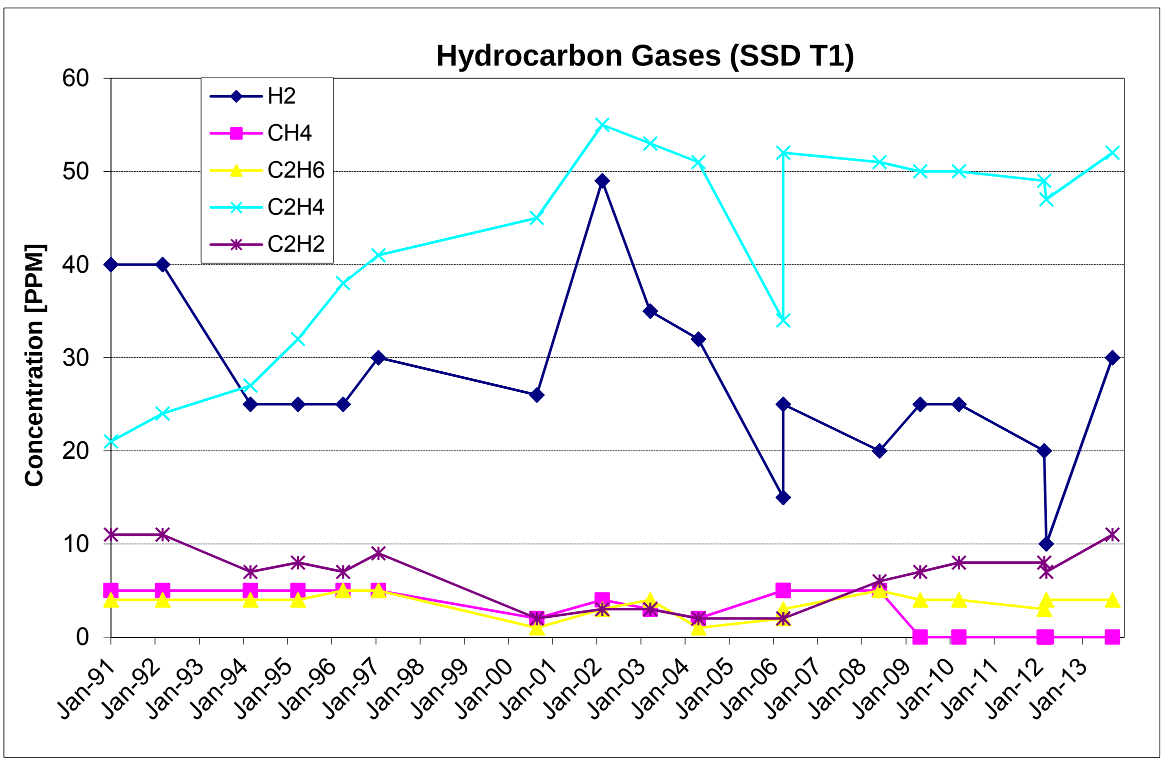


Figure 2 - Hydrocarbon Gas Concentrations

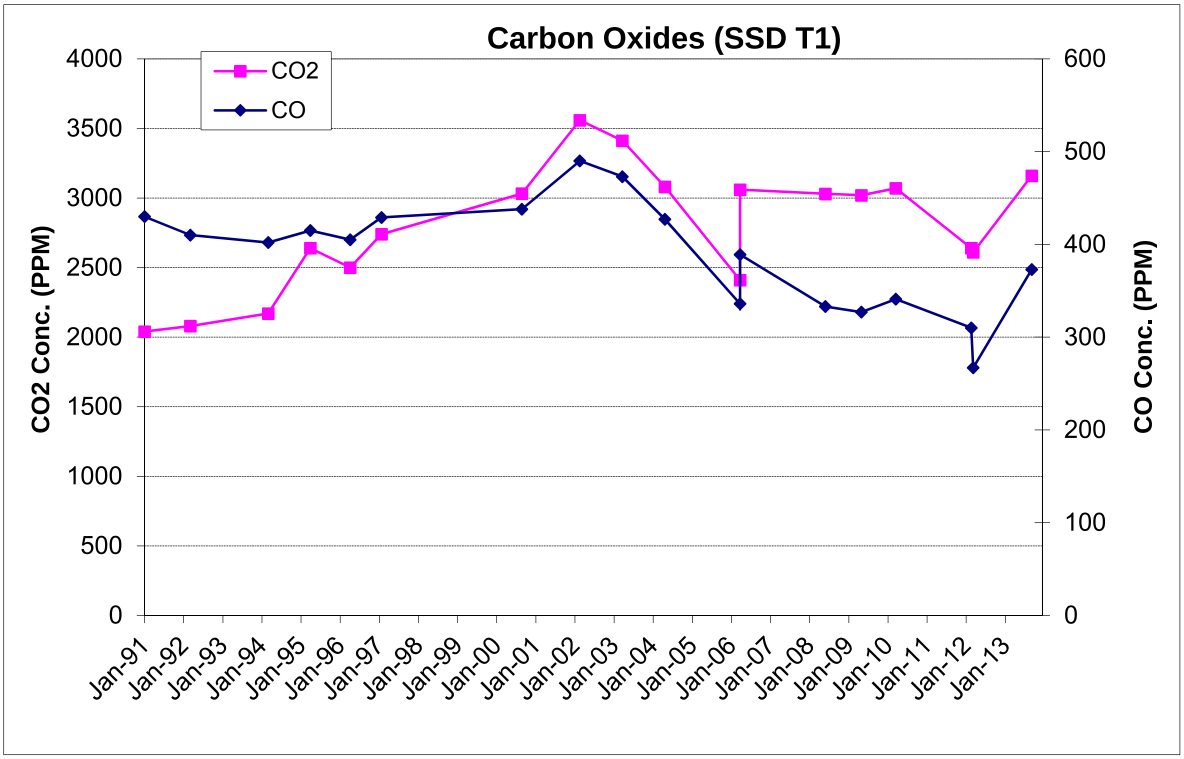


Figure 3 - Carbon Oxides Gas Concentrations

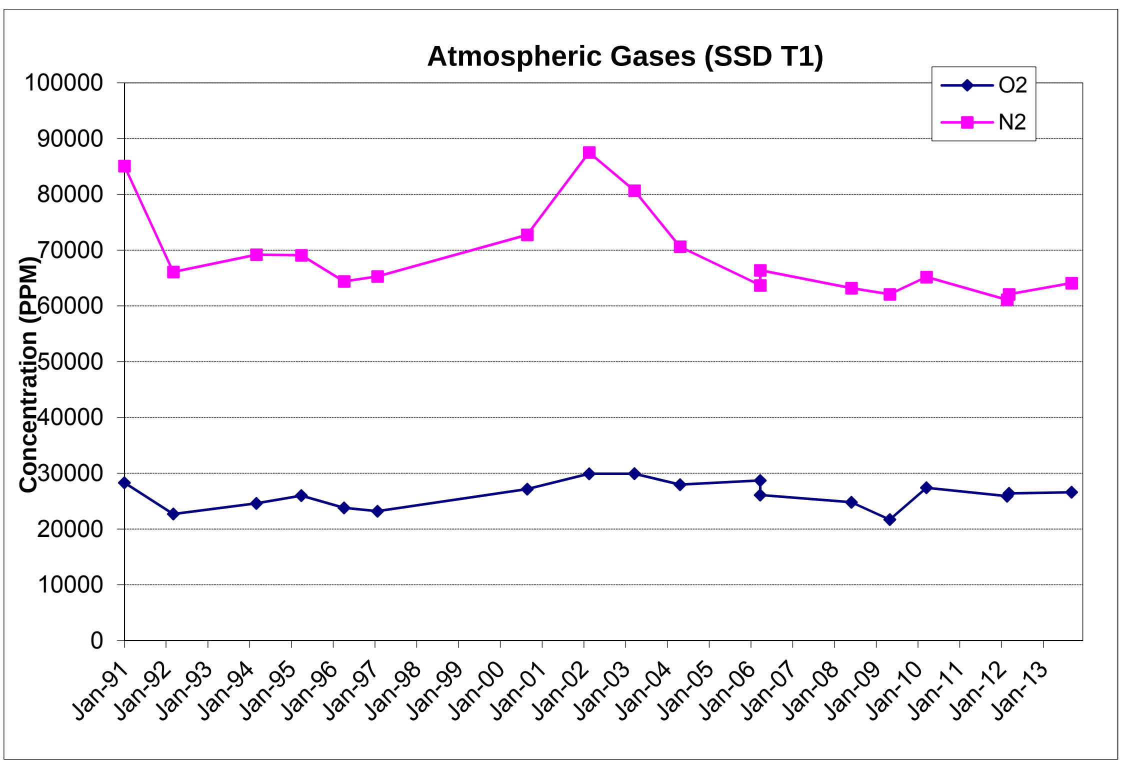


Figure 4 – Atmospheric Gases Concentrations

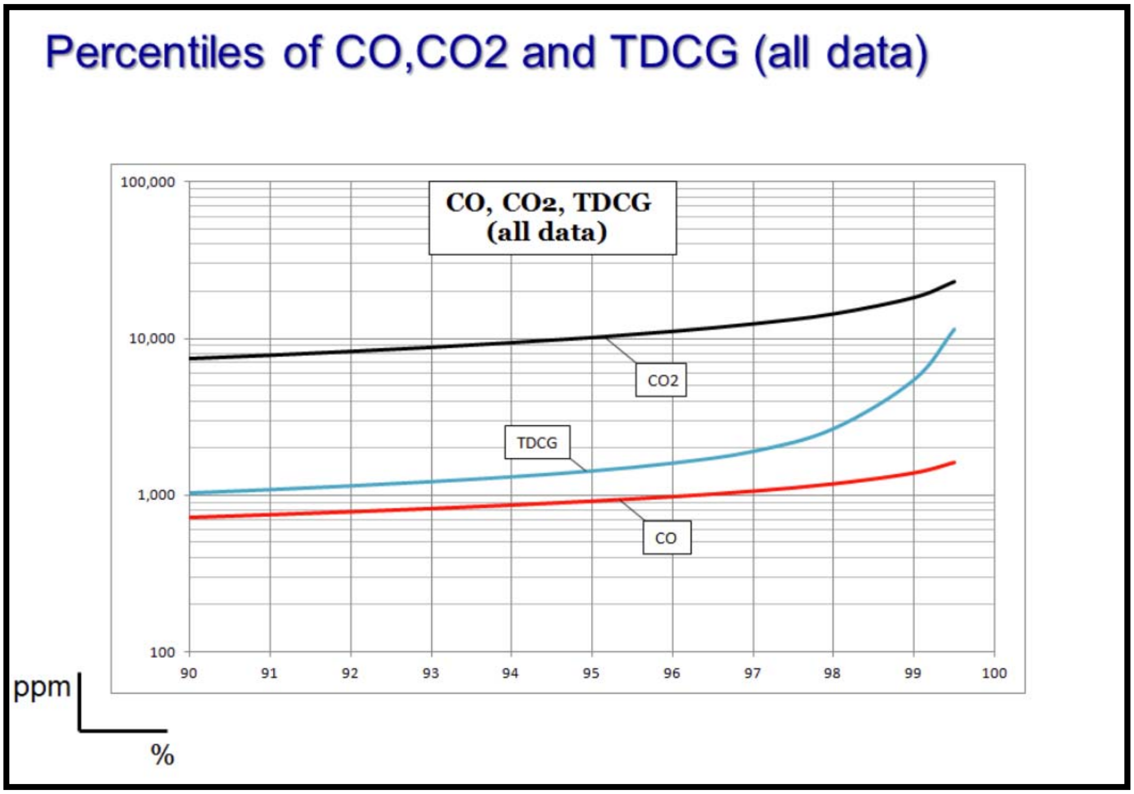


Figure 5 – IEEE Transformer Committee Carbon Oxide Survey Results

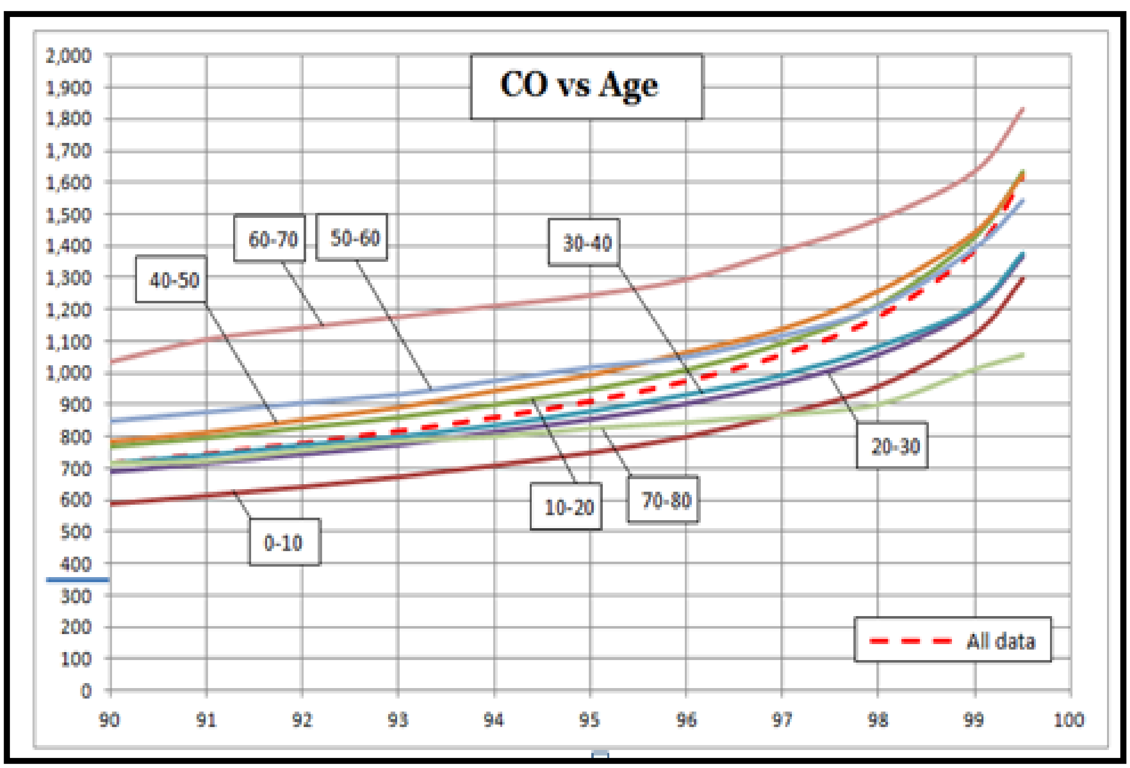


Figure 6 - IEEE Transformer Committee Carbon Oxide Survey Results (CO vs age)

4.2. SSD T4 – (CGE 288838)

Below is the report of the DGA data for the period of 1991 to 2013. The gas signatures for this transformer are shown in **Figure 7** to **Figure 9**.

The following is noted for the transformer DGA:

- The concentration of Hydrogen (H2) has been well below IEEE C57.104-2008 guide condition level 1 since 1991, the highest level is 30 ppm.
- The concentration of Methane (CH4) and Ethane (C2H6) have been steadily low for the period of the data provided. The Ethylene (C2H4) level is slightly above condition level one of the IEEE C57.104-2008 guide since 1991.
- The concentration of Acetylene (C2H2) has been above IEEE C57.104-2008 guide condition level 1 since 1991. The level went up and down since then but was almost stable around the 5ppm. This could be oil leaking from LTC diverter compartment.
- The carbon dioxide level has been below the IEEE C57.104-2008 guide condition level 1 for the time period provided. The carbon monoxide level is slightly above the IEEE C57.104-2008 guide condition level 1 between 1996 and 2004, however the level became normal after 2004. The ratio of CO2/CO is between 5 and 10. The normal CO2/CO ratios are typically in the range of 5-9. The ratio of the carbon oxides suggests that the concentrations are due to the normal aging process of the transformer.
- As can be seen from **Figure 5 & 6**, the 90^{th} percentile levels are 700 ppm and 7500 for CO and CO2 respectively. The 90^{th} percentile is about 700 ppm for the CO distribution by age categories and for 30 – 40 years category. The history gassing on this transformer was around 450 ppm and 3000 ppm for CO and CO2 respectively. Thus these levels are below the 90^{th} percentile of the IEEE data for the age of this unit.
- The presence of large concentrations of oxygen in the oil can promote the formation of acids in the oil and cellulose and accelerate the aging rate of the cellulose insulation. It is recommended that the concentration of oxygen in the transformer be less than 2000 ppm (Refer to CIGRE report 323 – Aging of Cellulose in Mineral-Oil Insulated Transformers). The transformer maintenance record (09/06/2012) provided by the customer does not mention if the oil had ever been vacuum processed since 1991. The oil samples from this transformer have consistently shown very high oxygen concentrations (>20,000 ppm) of oxygen. The source of this high oxygen is the free-breathing oil conservator. To reduce the oxygen in the transformer oil and eliminate the uncertainty concerning the gas generation, it is recommended to add a conservator diaphragm. The diaphragm prevents oil from coming in contact with the air. This will prevent moisture, excessive atmospheric gases from dissolving into the oil and it also helps to keep all gases generated by the transformer in oil for more accurate diagnostics.

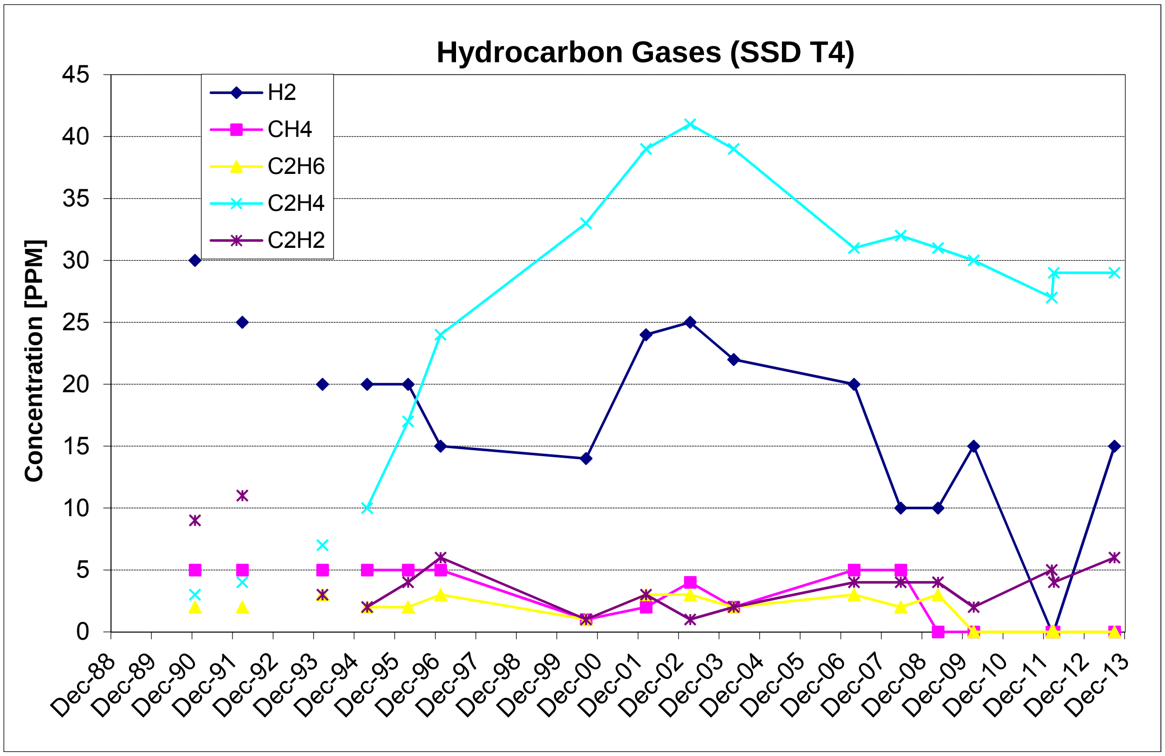


Figure 7 - Hydrocarbon Gas Concentrations

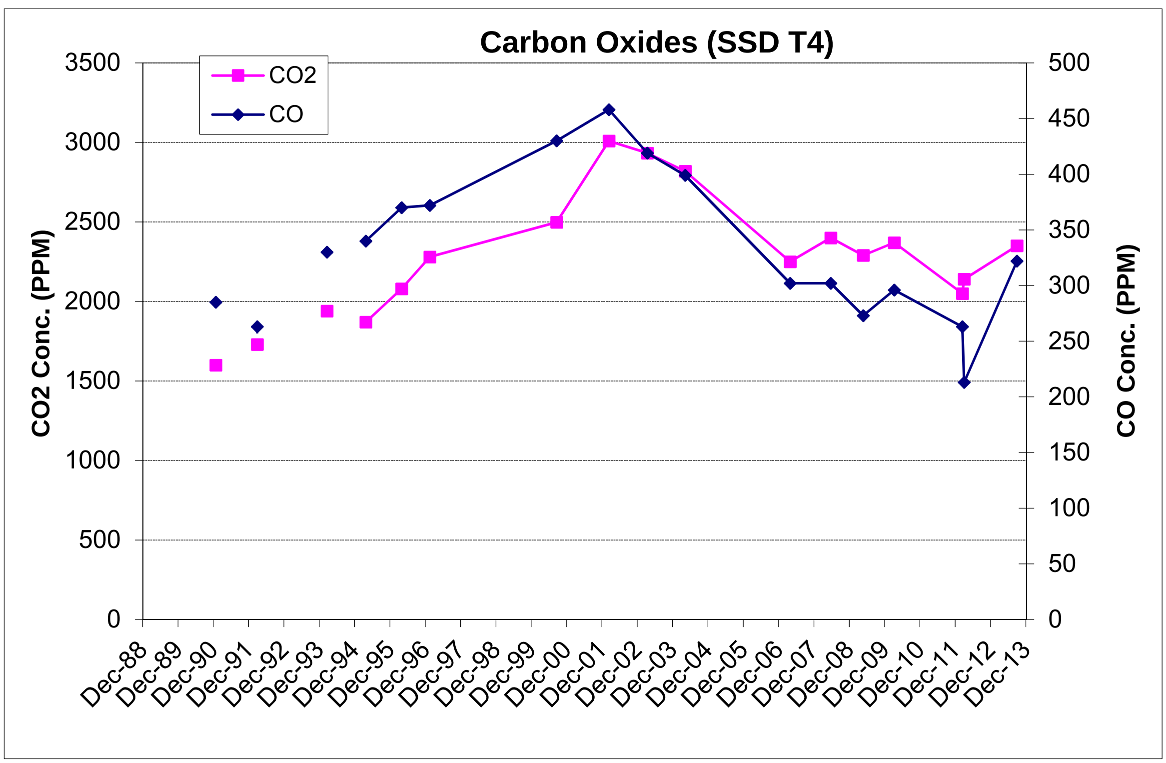


Figure 8 - Carbon Oxides Gas Concentrations

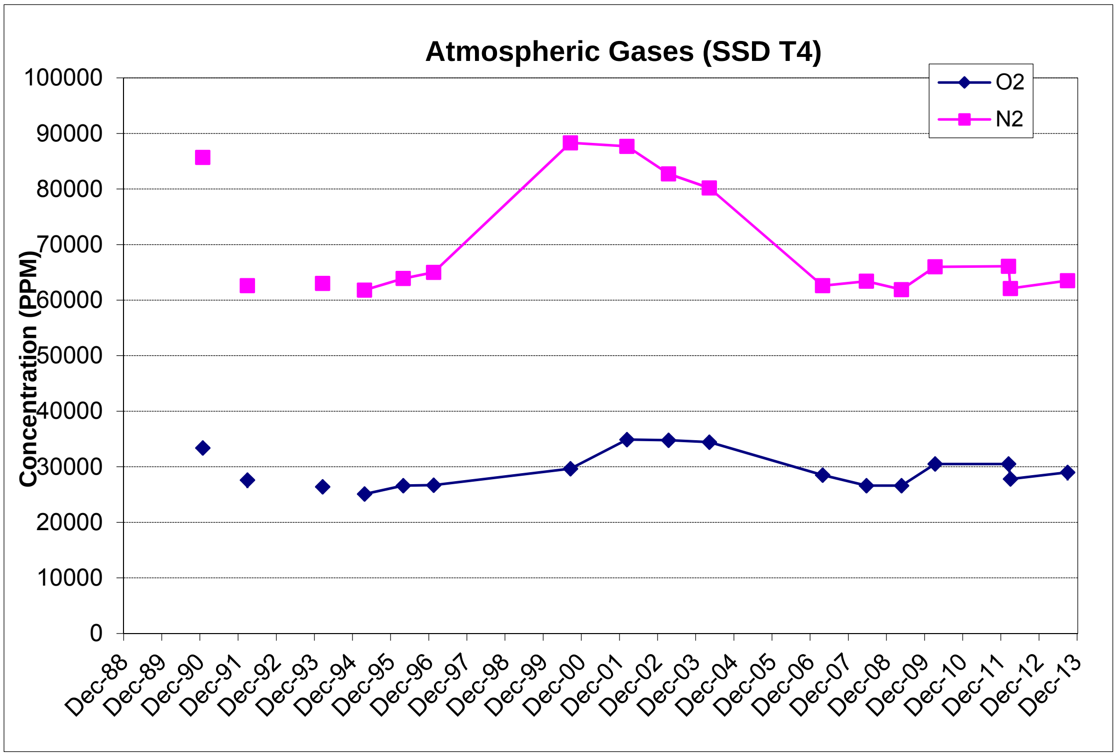


Figure 9 – Atmospheric Gases Concentrations

4.3. STB T1 – (CGE 288894)

Below is the report of the DGA data for the period of 1977 to 2013. The gas signatures for this transformer are shown in **Figure 10** to **Figure 12**.

The following is noted for the transformer DGA:

- The concentration of Hydrogen (H2) has been well below IEEE C57.104-2008 guide condition level 1 since 1977, the highest level is 75 ppm in 1979.
- The concentration of Methane (CH4) and Ethane (C2H6) have been steadily low for the period of the data provided. The Ethylene (C2H4) level has been below condition level 1 of the IEEE C57.104-2008 guide since 1977, except one sample (67 ppm) in 2009.
- The concentration of Acetylene (C2H2) has been below IEEE C57.104-2008 guide condition level 1 since 2009. However the DGA sample for the year 1979 shows high level of C2H2. This could be a bad oil sample.
- The carbon dioxide level has been above the IEEE C57.104-2008 guide condition level 1 for the most of time period provided. The carbon monoxide level is above the IEEE C57.104-2008 guide condition level 1 for most of time as well. However the ratio of CO2/CO is between 4 and 9. The normal CO2/CO ratios are typically in the range of 5-9. The ratio of the carbon oxides suggests that the concentrations are due to the normal aging process of the transformer.
- As can be seen from **Figure 5 & 6**, the 90^{th} percentile levels are 700 ppm and 7500 for CO and CO2 respectively. The 90^{th} percentile is about 700 ppm for the CO distribution by age categories and for 30 – 40 years category. The history gassing on this transformer was around 590 ppm and 4400 ppm for CO and CO2 respectively. Thus these levels are below the 90^{th} percentile of the IEEE data for the age of this unit.
- The presence of large concentrations of oxygen in the oil can promote the formation of acids in the oil and cellulose and accelerate the aging rate of the cellulose insulation. It is recommended that the concentration of oxygen in the transformer be less than 2000 ppm (Refer to CIGRE report 323 – Aging of Cellulose in Mineral-Oil Insulated Transformers). The transformer maintenance record (09/22/2011) provided by the customer does not mention if the oil had ever been vacuum processed since 1991. The oil samples from this transformer have consistently shown very high oxygen concentrations (>20,000 ppm) of oxygen. The source of this high oxygen is the free-breathing oil conservator. To reduce the oxygen in the transformer oil and eliminate the uncertainty concerning the gas generation, it is recommended to add a conservator diaphragm. The diaphragm prevents oil from coming in contact with the air. This will prevent moisture, excessive atmospheric gases from dissolving into the oil and it also helps to keep all gases generated by the transformer in oil for more accurate diagnostics

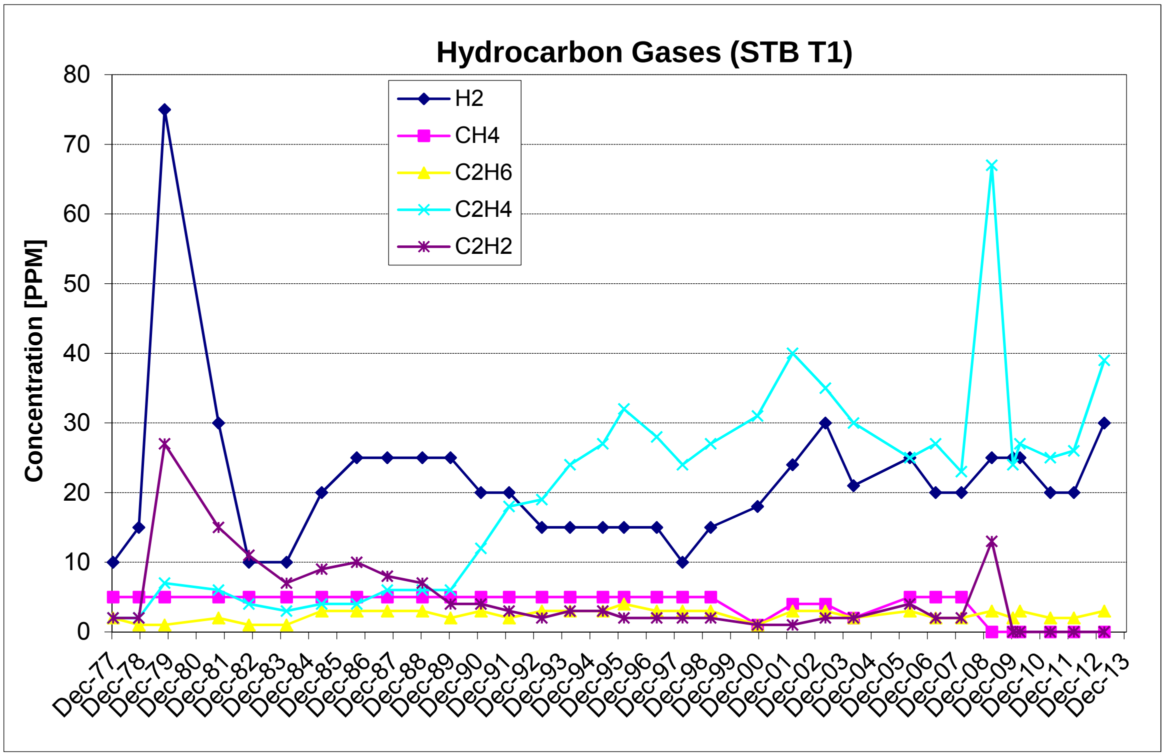


Figure 10 - Hydrocarbon Gas Concentrations

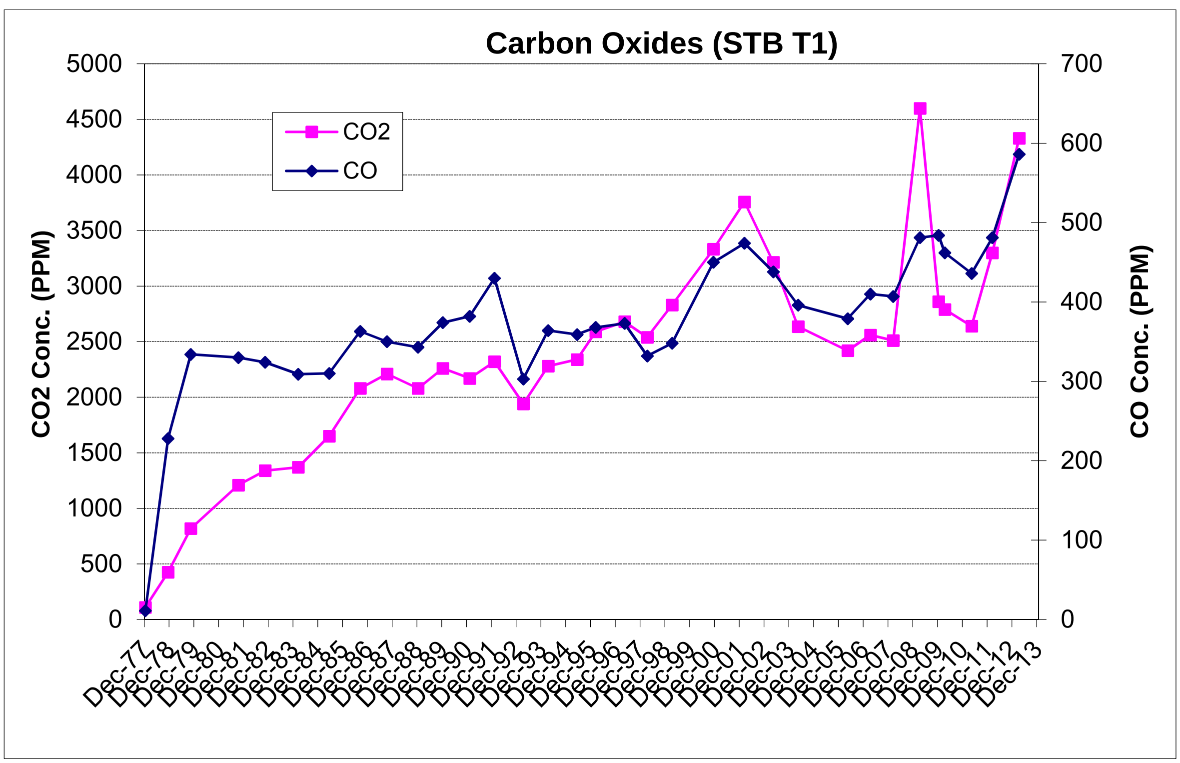


Figure 11 - Carbon Oxides Gas Concentrations

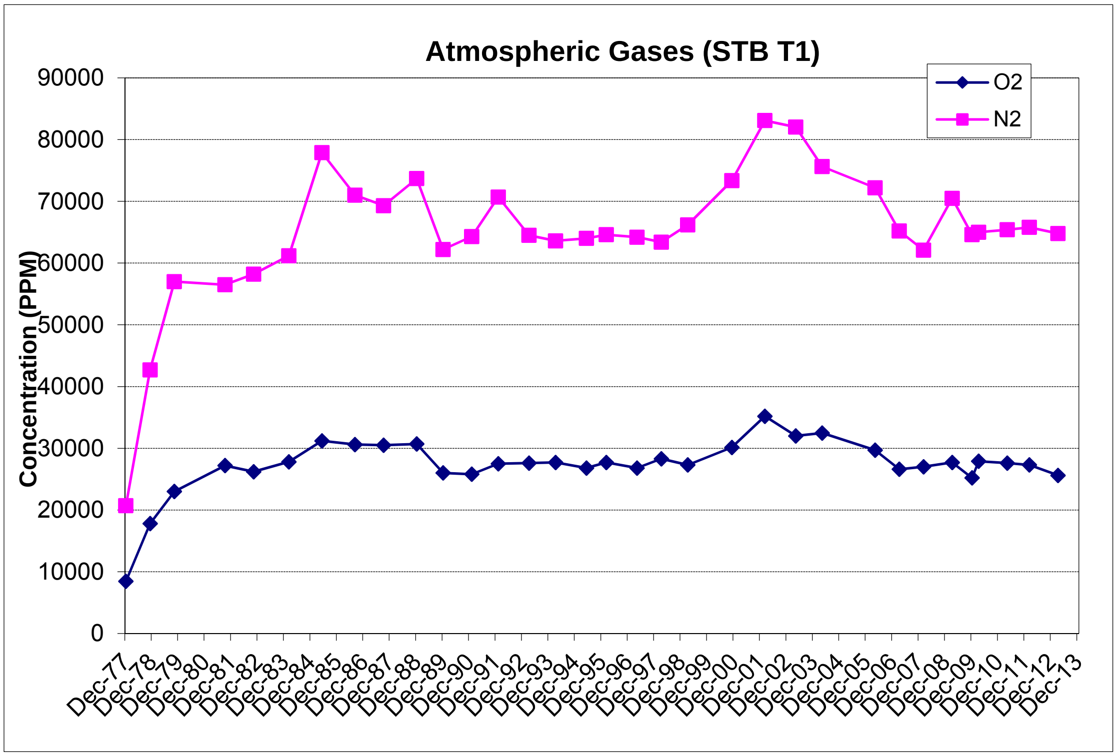


Figure 12 – Atmospheric Gases Concentrations

4.4. STB T2 – (CGE 288839)

Below is the report of the DGA data for the period of 1977 to 2013. The gas signatures for this transformer are shown in **Figure 13** to **Figure 15**.

The following is noted for the transformer DGA:

- The concentration of Hydrogen (H2) has been well below IEEE C57.104-2008 guide condition level 1 since 1977, the highest level is 50 ppm in 1987.
- The concentration of Methane (CH4) and Ethane (C2H6) have been steadily low for the period of the data provided. The Ethylene (C2H4) level has been in condition level 2 of the IEEE C57.104-2008 guide (50 ppm) since 2000.
- The transformer has consistently shown high concentrations (>20 ppm) of Acetylene (C2H2) since 1986, which is far above the IEEE C57.104-2008 guide condition level 2. The high concentration of C2H2 indicates that possible high energy arcing occurred somewhere inside the transformer. The other reason could be oil leaking from LTC diverter compartment. The Acetylene levels are about 10ppm foe few years now. This needs to be monitored closely. Any sudden increase of Acetylene needs to be investigated.
- The carbon dioxide level has been above the IEEE C57.104-2008 guide condition level 1 for the most of time period provided. The carbon monoxide level is above the IEEE C57.104-2008 guide condition level 1 for most of time as well. However the ratio of CO2/CO is between 5 and 10. The normal CO2/CO ratios are typically in the range of 5-9. The ratio of the carbon oxides suggests that the concentrations are due to the normal aging process of the transformer.
- As can be seen from **Figure 5 & 6**, the 90^{th} percentile levels are 700 ppm and 7500 for CO and CO2 respectively. The 90^{th} percentile is about 700 ppm for the CO distribution by age categories and for 30 – 40 years category. The history gassing on this transformer was around 560 ppm and 5500 ppm for CO and CO2 respectively. Thus these levels are below the 90^{th} percentile of the IEEE data for the age of this unit.
- The presence of large concentrations of oxygen in the oil can promote the formation of acids in the oil and cellulose and accelerate the aging rate of the cellulose insulation. It is recommended that the concentration of oxygen in the transformer be less than 2000 ppm (Refer to CIGRE report 323 – Aging of Cellulose in Mineral-Oil Insulated Transformers). It is unknown if the oil had ever been vacuum processed since 1977. The oil samples from this transformer have consistently shown very high oxygen concentrations (>20,000 ppm) of oxygen. The source of this high oxygen is the free-breathing oil conservator. To reduce the oxygen in the transformer oil and eliminate the uncertainty concerning the gas generation, it is recommended to add a conservator diaphragm. The diaphragm prevents oil from coming in contact with the air. This will prevent moisture, excessive atmospheric gases from dissolving into the oil and it also helps to keep all gases generated by the transformer in oil for more accurate diagnostics

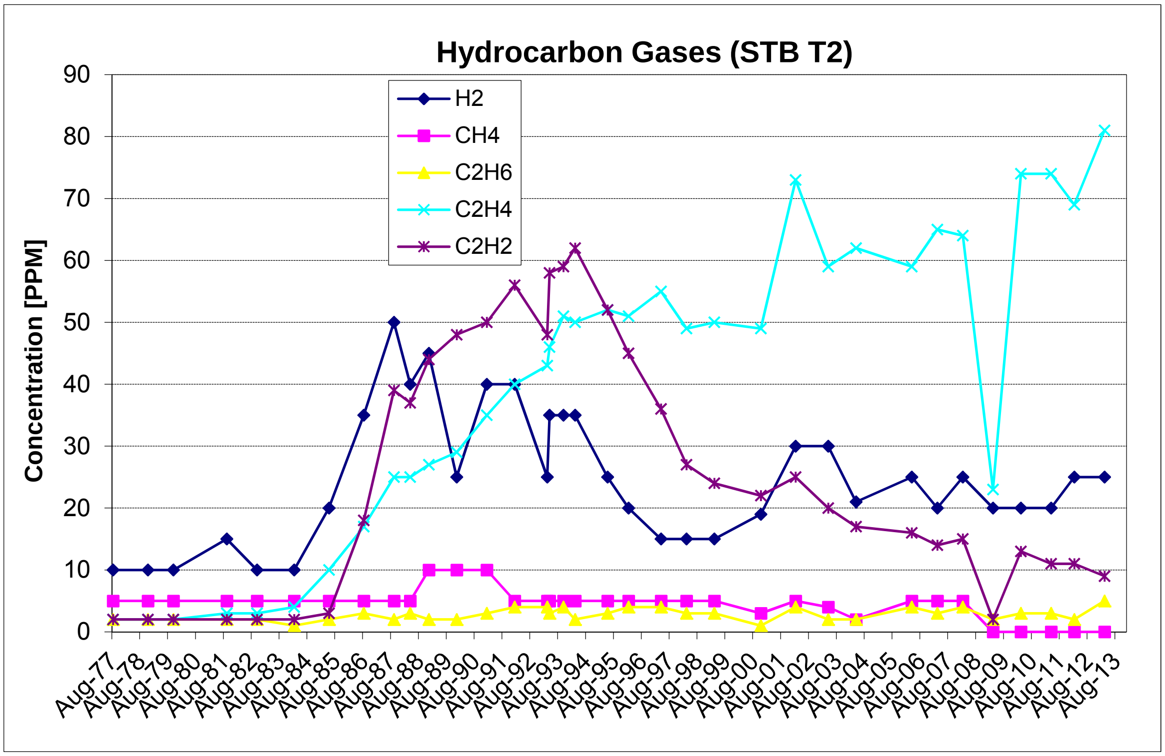


Figure 13 - Hydrocarbon Gas Concentrations

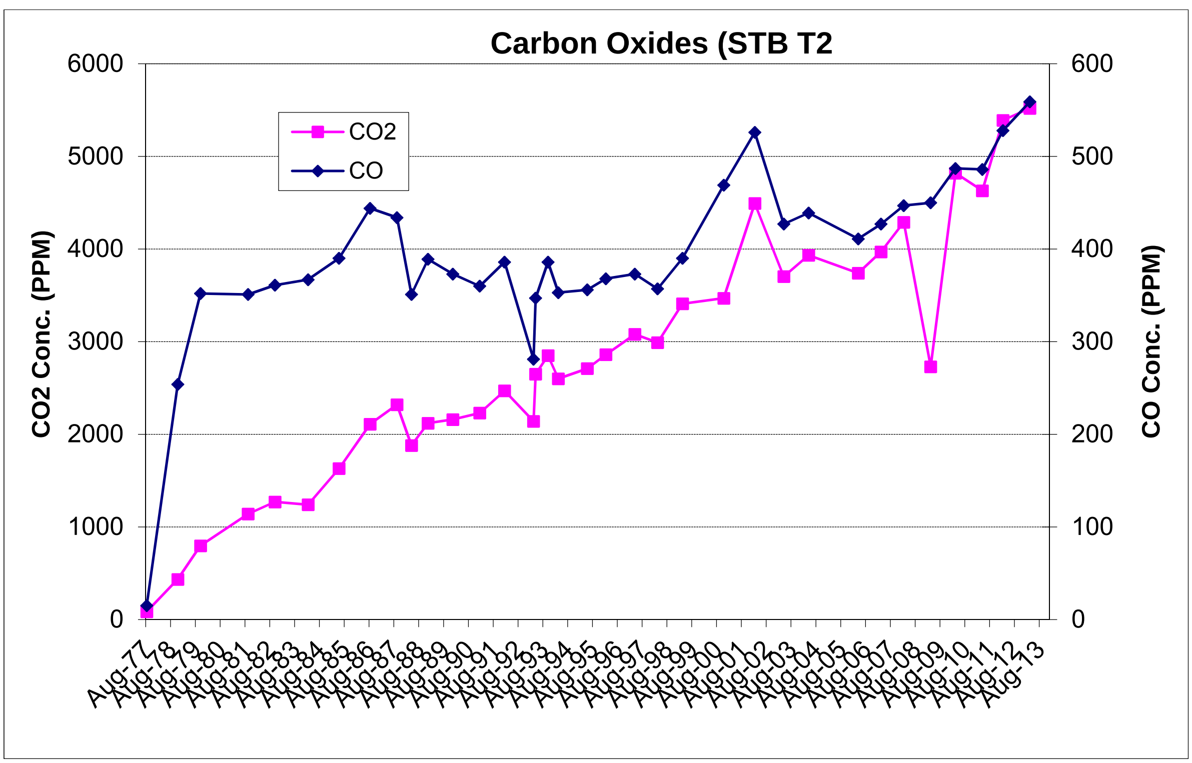


Figure 14 - Carbon Oxides Gas Concentrations

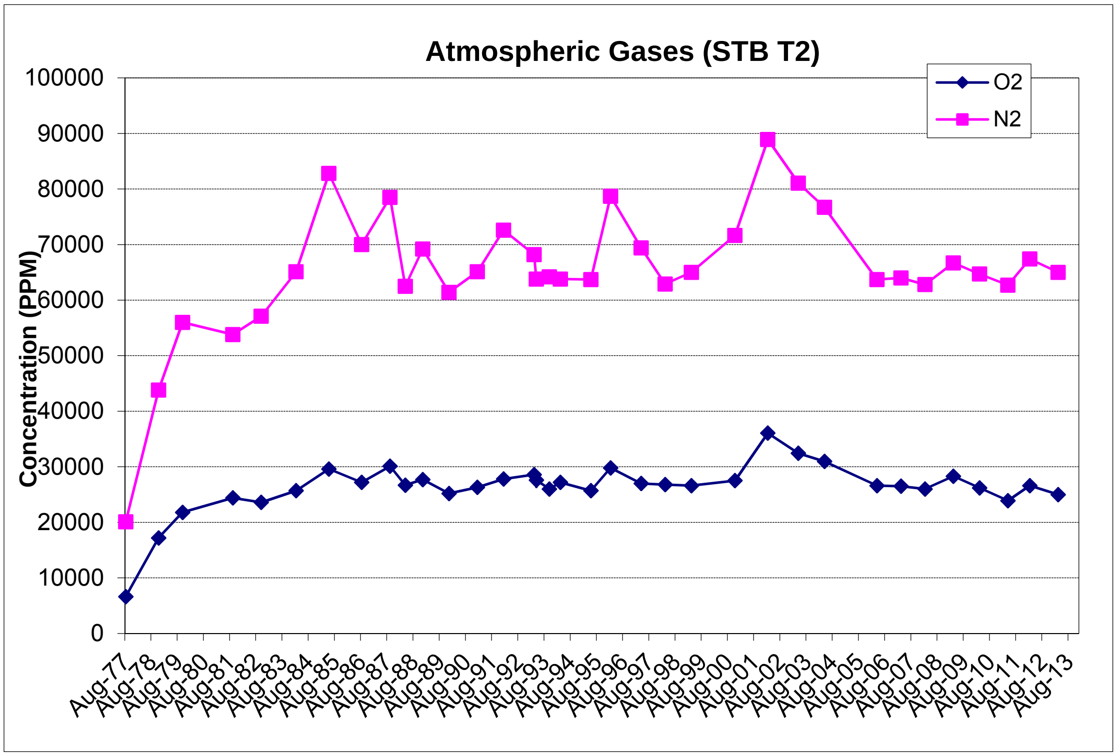


Figure 15 – Atmospheric Gases Concentrations

5. General Oil Quality

5.1. SSD T1 – (CGE 289147)

2.1.1 Main Tank

Below is the report of the oil quality data results from 2009 to 2013. The history of the oil quality data measured for this transformer is shown in **Table 8**.

The following can be observed:

- The latest measured breakdown voltage (52.0 kV/mm on 09/11/2013) is above the minimum requirement (30kV/mm) as outlined by Doble Engineering for ≥ 230kV transformers with service aged insulating oil based on D877 method. However ASTM D1816-97 is recommended for testing fluid that is being processed into transformers and load tap changers. The gap distance standard settings are 1 mm and 2 mm.

- The interfacial tension values are around 28.0 dynes/cm2 which are below the 32 dynes/cm2 limit recommended by IEEE C57.106-2002 for ≥ 230kV transformers. Lower values may indicate oil soluble contaminants and oxidation products in oil.

- The oxidation inhibitor values were not measured since 2009. The acceptable range is between 0.08 and 0.30%. Oxygen inhibitors are helpful to minimize the effects of oxidation of oil. The first choice of attack by oxygen in the oil is the inhibitor molecules. This keeps the oil free from oxidation and its harmful by-products. As transformer ages, the oxidation inhibitor is used up and need to be replaced.

- The measured Acid Numbers for the oil samples in the past years are all below the recommended limits (0.10 mg KOH/g) by IEEE C57.106-2002 for ≥ 230kV transformers.

- The measured power factor values at 25/100°C are all below the suggested limits as outlined in IEEE C57.106-2002 for continue use of service-aged insulating oil.

- IEEE C57.106-2002 Table 5 recommends that the maximum limit of water content in oil for 230kV transformers is not to exceed 10 ppm or 5% saturation at 50ºC. The oil samples taken from the main tank show moisture content of less than 10 ppm.

Table 8 - Oil Quality Data (Main Tank)

Sample Date	Fluid Temp (°C)	Dielectric Breakdown D877 (kV)	Acid Number D974 (mg KOH/g)	Interfacial Tension D971 (dynes/cm)	Visual Condition D1524	Power Factor D924 (%) 25°C / 100 C		Water (ppm)	% Satur.	Inhibitor (%)
05/05/2009	30	55	0.03	28.6	Clear	0.062	1.38	2	2	-
03/22/2010	25	45	0.03	27.8	Clear	0.035	1.28	5	7	-
02/24/2012	20	59	0.03	26.9	Clear	0.123	2.62	2	4	-
03/13/2012	20	49	0.03	27.5	Clear	0.115	3.28	2	4	-
09/11/2013	35	52	0.03	28.1	Clear	0.166	2.94	3	3	-

2.1.2 LTC Tank

Below is the report of the LTC oil quality data results for 2007, 2008 and 2012. The oil quality test is not available for LTC-B,C in 2007. The history of the oil quality data measured for LTC-A,B,C is shown in **Table 9** below.

The following can be observed:

- The measured breakdown voltage (around 22.0 kV/mm for LTC-A,B,C) is below the minimum requirement (28 kV/mm for 1 mm gap and 45 kV/mm for 2 mm gap) as outlined by IEEE C57.106-2002 for LTC mounted at line end with ≥ 69 kV rating and for service aged insulating oil in LTC based on D1816 method. However the oil test reports do not mention gap distance. (1 mm or 2 mm). If the dielectric strength of the oil drops below the suggested values given in IEEE C57.106-2002, the oil should be reconditioned or changed.

- The interfacial tension values are around 36.0 dynes/cm2. However IEEE C57.106-2002 does not specify any IFT limits for continued use of service aged insulating oil for load tap changers.

- The measured Acid Numbers for the oil samples are all below 0.10 mg KOH/g. However IEEE C57.106-2002 does not specify any Acid number limits for load tap changers

- IEEE C57.106-2002 Table 12 recommends that the maximum limit of water content in oil for LTC is not to exceed 25 ppm. The oil samples taken from the LTC-A tank does show moisture content of more than 25 ppm. If the water content exceeds the values given in IEEE C57.106-2002, the oil should be reconditioned or changed.

Table 9 - Oil Quality Data (LTC Tank)

Sample Date	LTC ID	Fluid Temp. (^oC)	Dielectric Breakdown D1816 (kV)	Acid Number D974 (mg KOH/g)	Interfacial Tension D971 (dynes/cm)	Color # D1500	Water (ppm)
06/27/2007	A	30	14	0.012	35.0	<3.0	43
	B	-	-	-	-	-	-
	C	-	-	-	-	-	-
04/29/2008	A	45	25	0.016	36.3	<2.0	14
	B	35	22	0.014	35.5	<2.5	13
	C	35	22	0.016	36.8	<2.5	9
10/02/2012	A	35	22	0.011	38.7	<4.0	26
	B	35	22	0.015	38.1	<2.5	16
	C	35	23	0.014	38.3	<4.0	18

5.2. SSD T4 – (CGE 288838)

2.2.1 Main Tank

Below is the report of the oil quality data results from 2009 to 2013. The history of the oil quality data measured for this transformer is shown in **Table 10**.

The following can be observed:

- The latest measured breakdown voltage (52.0 kV/mm on 09/11/2013) is above the minimum requirement (30kV/mm) as outlined by Doble Engineering for 230kV transformers with service aged insulating oil based on D877 method. However ASTM D1816-97 is recommended for testing fluid that is being processed into transformers and load tap changers. The gap distance standard settings are 1 mm and 2 mm.

- The interfacial tension values are around 33.6 dynes/cm2 which is slightly above the 32 dynes/cm2 limit recommended by IEEE C57.106-2002 for 230kV transformers. Lower values may indicate oil soluble contaminants and oxidation products in oil.

- The oxidation inhibitor values were not measured since 2009. The acceptable range is between 0.08 and 0.30%. Oxygen inhibitors are helpful to minimize the effects of oxidation of oil. The first choice of attack by oxygen in the oil is the inhibitor molecules. This keeps the oil free from oxidation and its harmful by-products. As transformer ages, the oxidation inhibitor is used up and need to be replaced. It is highly recommended to add oxidation inhibitor in the oil.

- The measured Acid Numbers for the oil samples in the past years are all below the recommended limits (0.10 mg KOH/g) by IEEE C57.106-2002 for 230kV transformers.

- The measured power factor values at 25/100°C are all below the suggested limits as outlined in IEEE C57.106-2002 for continue use of service-aged insulating oil.

- IEEE C57.106-2002 Table 5 recommends that the maximum limit of water content in oil for 230kV transformers is not to exceed 10 ppm or 5% saturation at 50ºC. The oil samples taken from the main tank show moisture content of less than 10 ppm.

Table 10 - Oil Quality Data (Main Tank)

Sample Date	Fluid Temp (°C)	Dielectric Breakdown D877 (kV)	Acid Number D974 (mg KOH/g)	Interfacial Tension D971 (dynes/cm)	Visual Condition D1524	Power Factor D924 (%) 25°C / 100 C		Water (ppm)	% Satur.	Inhibitor (%)
05/05/2009	34	56	0.01	33.6	Clear	0.066	1.04	2	2	-
03/22/2010	30	36	0.01	31.7	Clear	0.015	0.63	7	8	-
02/24/2012	25	33	0.02	32.0	Clear	0.042	1.24	2	3	-
03/13/2012	25	57	0.02	33.1	Clear	0.054	1.17	2	3	-
09/11/2013	42	52	0.02	33.6	Clear	0.054	1.91	4	3	-

2.2.2 LTC Tank

Oil was replaced with new oil for these tap changers in 2013. The history of the oil quality data measured for LTC-A,B,C is shown in **Table 11** below. The report of the LTC oil quality data results will only consider the 2014 results.

The following can be observed:

- The measured breakdown voltage (between 20.0 kV/mm and 21.0 kV/mm for LTC-A,B,C) is below the minimum requirement (28 kV/mm for 1 mm gap and 45 kV/mm for 2 mm gap) as outlined by IEEE C57.106-2002 for LTC mounted at line end with ≥ 69 kV rating and for service- aged insulating oil in LTC based on D1816 method. However the oil test reports do not mention gap distance. (1 mm or 2 mm?). The dielectric strength of the oil is below the suggested values given in IEEE C57.106-2002, the oil should be reconditioned or replaced.

- The interfacial tension values are around 45 dynes/cm2. However IEEE C57.106-2002 does not specify any IFT limits for continued use of service aged insulating oil for load tap changers.

- The measured Acid Numbers for the oil samples are all below 0.10 mg KOH/g. However IEEE C57.106-2002 does not specify any Acid number limits for load tap changers

- IEEE C57.106-2002 Table 12 recommends that the maximum limit of water content in oil for LTC is not to exceed 25 ppm. The oil samples taken from the LTC tank show moisture content much less than 25 ppm.

Table 11 - Oil Quality Data (LTC Tank)

Sample Date	LTC ID	Fluid Temp. (^{o}C)	Dielectric Breakdown D1816 (kV)	Acid Number D974 (mg KOH/g)	Interfacial Tension D971 (dynes/cm)	Color # D1500	Water (ppm)
04/29/2008	A	33	-	-	-	-	21
	B	33	21	0.014	37.3	<4.5	18
	C	33	22	0.013	37.9	<4.5	14
08/28/2012	A	45	18	0.011	39.1	<4.0	18
	B	-	-	-	-	-	-
	C	-	-	-	-	-	-
10/02/2012	A	40	22	0.012	39.7	<4.0	11
	B	40	25	0.011	39.4	<4.0	12
	C	40	29	0.014	39.4	<2.5	24
01/17/2013	A	30	23	0.014	38.6	>5.0	14
	B	30	22	0.013	38.2	>5.0	9
	C	30	22	0.014	38.7	>5.0	10
01/28/2014	A	32	20	0.004	44.6	<2.0	2
	B	32	20	0.003	44.7	<2.0	5
	C	32	21	0.004	45.4	<1.5	2

5.3. STB T1 – (CGE 288894)

2.3.1 Main Tank

Below is the report of the oil quality data results from 2009 to 2013. The history of the oil quality data measured for this transformer is shown in **Table 12**.

The following can be observed:

- The latest measured breakdown voltage (62.0 kV/mm on 03/14/2013) is above the minimum requirement (30kV/mm) as outlined by Doble Engineering for 230kV transformers with service aged insulating oil based on D877 method. However ASTM D1816-97 is recommended for testing fluid that is being processed into transformers and load tap changers. The gap distance standard settings are 1 mm and 2 mm.

- The interfacial tension values are around 30.4 dynes/cm2 which is below the suggested limits (32 dynes/cm2) recommended by IEEE C57.106-2002 for 230kV transformers. Lower values may indicate oil soluble contaminants and oxidation products in oil.

- The oxidation inhibitor values were not measured since 2009. The acceptable range is between 0.08 and 0.30%. Oxygen inhibitors are helpful to minimize the effects of oxidation of oil. The first choice of attack by oxygen in the oil is the inhibitor molecules. This keeps the oil free from oxidation and its harmful by-products. As transformer ages, the oxidation inhibitor is used up and need to be replaced. It is highly recommended to add oxidation inhibitor in the oil.

- The measured Acid Numbers for the oil samples in the past years are all below the recommended limits (0.10 mg KOH/g) by IEEE C57.106-2002 for 230kV transformers.

- The measured power factor values at 25/100°C are all below the suggested limits as outlined in IEEE C57.106-2002 for continue use of service-aged insulating oil.

- IEEE C57.106-2002 Table 5 recommends that the maximum limit of water content in oil for 230kV transformers is not to exceed 10 ppm or 5% saturation at 50ºC. The oil samples taken from the main tank show moisture content of less than 10 ppm.

- The BDV measurement on 03/14/2012 (in RED) was based on D1816-2mm method.

Table 12 - Oil Quality Data (Main Tank)

Sample Date	Fluid Temp (°C)	Dielectric Breakdown D877 (kV)	Acid Number D974 (mg KOH/g)	Interfacial Tension D971 (dynes/cm)	Visual Condition D1524	Power Factor D924 (%) 25°C / 100 C		Water (ppm)	% Satur.	Inhibitor (%)
03/09/2009	35	53	0.02	32.6	Clear	0.043	0.98	2	2	-
03/15/2010	40	54	0.02	32.0	Clear	0.035	0.98	2	2	-
04/05/2011	40	45	0.02	31.0	Clear	0.065	1.49	4	3	-
02/13/2012	35	52	0.02	30.2	Clear	0.053	2.24	2	2	-
03/14/2013	40	62	0.02	30.4	Clear	0.058	1.39	3	2	-

2.3.2 LTC Tank

Oil was replaced with new oil for these tap changers in 2011. No data is available with the new oil. Below is the report of the LTC oil quality data results from 2007 to 2010. The history of the oil quality data measured for LTC-A,B,C is shown in **Table 13** below.

The following can be observed:

- The latest measured breakdown voltage is 30, 31 and 33 kV/mm for LTC-A,B,C. the suggested limits is 28 kV/mm for 1 mm gap and 45 kV/mm for 2 mm gap as outlined by IEEE C57.106-2002 for LTC mounted at line end with ≥ 69 kV rating and for service- aged insulating oil in LTC based on D1816 method. However the oil test reports do not mention gap distance. (1 mm or 2 mm?). If the dielectric strength of the oil drops below the suggested values given in IEEE C57.106-2002, the oil should be reconditioned or changed.

- The interfacial tension values are around 35.0 dynes/cm2. However IEEE C57.106-2002 does not specify any IFT limits for continued use of service aged insulating oil for load tap changers.
- The measured Acid Numbers for the oil samples are all below 0.10 mg KOH/g. However IEEE C57.106-2002 does not specify any Acid number limits for load tap changers
- IEEE C57.106-2002 Table 12 recommends that the maximum limit of water content in oil for LTC is not to exceed 25 ppm. The latest oil samples taken from the LTC tank show moisture content of less than 25 ppm. If the water content exceeds the values given in IEEE C57.106-2002, the oil should be reconditioned or changed.
- Note: The recorded temperature 22°C is much lower than the other phases.

Table 13 - Oil Quality Data (LTC Tank)

Sample Date	LTC ID	Fluid Temp. (°C)	Dielectric Breakdown D1816 (kV)	Acid Number D974 (mg KOH/g)	Interfacial Tension D971 (dynes/cm)	Color # D1500	Water (ppm)
08/06/2007	Left	45	22	0.027	35.6	<3.5	28
	Center	45	18	0.026	35.0	<3.5	29
	Right	45	24	0.026	33.9	<3.5	12
07/18/2008	Left	22	14	0.016	35.1	<2.0	42
	Center	72	14	0.016	34.4	<3.0	40
	Right	72	14	0.015	35.0	<2.5	41
05/27/2010	Left	-	31	0.016	35.5	<3.0	22
	Center	-	30	0.016	35.4	<3.5	15
	Right	-	33	0.016	35.7	<3.0	24

5.4. STB T2 – (CGE 288839)

2.4.1 Main Tank

Below is the report of the oil quality data results from 05/2009 to 09/2013. The history of the oil quality data measured for this transformer is shown in **Table 14**.

The following can be observed:

- The latest measured breakdown voltage (68.0 kV/mm on 03/14/2013) is above the minimum requirement (50kV/mm) as outlined in IEEE C57.106-2002 for 230kV transformers with service aged insulating oil based on D1816-2mm method.

- The interfacial tension values are around 28.7 dynes/cm2 which is below the suggested limits (32 dynes/cm2) recommended by IEEE C57.106-2002 for 230kV transformers. Lower values may indicate oil soluble contaminants and oxidation products in oil.
- The oxidation inhibitor values were not measured since 2009. The acceptable range is between 0.08 and 0.30%. Oxygen inhibitors are helpful to minimize the effects of oxidation of oil. The first choice of attack by oxygen in the oil is the inhibitor molecules. This keeps the oil free from oxidation and its harmful by-products. As transformer ages, the oxidation inhibitor is used up and need to be replaced. It is highly recommended to add oxidation inhibitor in the oil.
- The measured Acid Numbers for the oil samples in the past years are all below the recommended limits (0.10 mg KOH/g) by IEEE C57.106-2002 for 230kV transformers.
- The measured power factor values at 25/100°C are all below the suggested limits as outlined in IEEE C57.106-2002 for continue use of service-aged insulating oil.

- IEEE C57.106-2002 Table 5 recommends that the maximum limit of water content in oil for 230kV transformers is not to exceed 10 ppm or 5% saturation at 50ºC. The oil samples taken from the main tank show moisture content of less than 10 ppm.
- The BDV measurement on 03/14/2012 (in RED) was based on D1816 method.

Table 14 - Oil Quality Data (Main Tank)

Sample Date	Fluid Temp (°C)	Dielectric Breakdown D877 (kV)	Acid Number D974 (mg KOH/g)	Interfacial Tension D971 (dynes/cm)	Visual Condition D1524	Power Factor D924 (%) 25°C / 100 C		Water (ppm)	% Satur.	Inhibitor (%)
03/09/2009	40	56	0.02	29.4	Clear	0.074	1.53	3	2	-
03/15/2010	49	56	0.02	29.4	Clear	0.059	1.59	2	1	-
04/05/2011	48	44	0.02	28.4	Clear	0.132	2.60	6	4	-
02/13/2012	43	45	0.03	27.1	Clear	0.098	2.98	3	2	-
03/14/2013	49	**68**	0.03	28.7	Clear	0.090	1.86	2	1	-

2.4.2 LTC Tank

Below is the report of the LTC oil quality data results from 2007 to 2011. The history of the oil quality data measured for LTC-A,B,C is shown in **Table 15** below.

The following can be observed:

- The latest measured breakdown voltage is 17, 21 and 23 kV/mm for LTC-A,B,C. the suggested minimum limits is 28 kV/mm for 1 mm gap and 45 kV/mm for 2 mm gap as outlined by IEEE C57.106-2002 for LTC mounted at line end with ≥ 69 kV rating and for service- aged insulating oil in LTC based on D1816 method. However the oil test reports do not mention gap distance. (1 mm or 2 mm?). The dielectric strength of the oil is below the suggested values given in IEEE C57.106-2002, the oil should be reconditioned or replaced.

- The interfacial tension values are around 34.0 dynes/cm2. However IEEE C57.106-2002 does not specify any IFT limits for continued use of service aged insulating oil for load tap changers.
- The measured Acid Numbers for the oil samples are all below 0.10 mg KOH/g. However IEEE C57.106-2002 does not specify any Acid number limits for load tap changers
- IEEE C57.106-2002 Table 12 recommends that the maximum limit of water content in oil for LTC is not to exceed 25 ppm. The latest oil samples taken from the LTC tank show moisture content of more than 25 ppm for all three LTCs. If the water content exceeds the values given in IEEE C57.106-2002, the oil should be reconditioned or changed.

Table 15 - Oil Quality Data (LTC Tank)

Sample Date	LTC ID	Fluid Temp. (^oC)	Dielectric Breakdown D1816 (kV)	Acid Number D974 (mg KOH/g)	Interfacial Tension D971 (dynes/cm)	Color # D1500	Water (ppm)
08/07/2007	Left	52	25	0.022	34.4	<3.5	16
	Center	52	20	0.024	33.8	<3.5	12
	Right	52	23	0.022	35.0	<3.5	19
07/16/2008	Left	42	17	0.015	35.5	<2.5	44
	Center	42	22	0.015	34.5	<2.5	35
	Right	42	25	0.018	32.6	<2.5	33
08/18/2011	Left	52	23	0.015	33.8	<2.5	34
	Center	52	17	0.016	33.8	<2.5	32
	Right	52	21	0.018	34.1	5.0	42

6. Transformer Power Factor Measurement

6.1. SSD T1 – (CGE 289147)

Doble test was available only for 2007. The overall test and bushings test results for this transformer are shown in **Tables 16** below.

The following is observed:

- The winding power factor values (CH & CT) are below 0.5%. The negative P.F for CHT is most likely because of the ground shield between the LV winding and the TV winding**. Table 16-1**
- The C1 power factor and capacitance values for HV & LV bushings are all acceptable. IEEE Std C57.19.01-2000 specifies a limit of 0.5% for C1 power factor for oil impregnated paper insulated bushings. ABB recommends that the bushings be replaced whenever the power factor is double the nameplate value. **Table 16-2**
- The measured C2 capacitance for HV & LV bushings is higher than the nameplate values by more than 10%. This needs to be compared to initial benchmark test results. **Table 16-3**
- The hot collar tests for TV bushings and neutral bushing are below recommended limit (0.1 W at 10 kV). **Table 16-4**
- The Doble exciting current test are normal. **Table 16-5**

Table 16-1 – Doble Overall Test Results (2007)

Meas.	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap(pF)	IR_{auto}	IR_{man}
CH + CHT	10.016	116.87	3.600	0.31	1.00	31000.6		
CH	10.010	116.15	3.605	0.31	1.00	30808.1	G	
CHT(UST)	10.008	0.7090	-000.02	-0.28	1.00	188.02	I	
CHT		0.720	-0.005	-0.07	1.00	192.500	I	
CT + CHT	5.001	132.63	5.960	0.45	1.00	35180.3		
CT	5.003	131.92	5.973	0.45	1.00	34991.9	G	
CHT(UST)	5.004	0.7070	-000.02	-0.28	1.00	187.58	I	
CHT		0.710	-0.013	-0.18	1.00	188.400	I	

Table 16-2 – Doble Bushing Test Results (2007)

Bushing C1

ID	Serial #	NP %PF	NP Cap	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap (pF)	IR_{auto}	IR_{man}
H1	250663	.28	431	10.006	1.599	0.0400	0.25	1.00	424.25	G	
H2	250881	.27	422	10.005	1.571	0.0350	0.22	1.00	416.75	G	
H3	251439	.27	420	10.005	1.564	0.0330	0.21	1.00	414.79	G	
X1	251307	.24	359	10.005	1.348	0.0310	0.23	1.00	357.50	G	
X2	251308	.24	359	10.005	1.350	0.0300	0.22	1.00	358.05	G	
X3	251311	.24	344	10.006	1.295	0.0180	0.14	1.00	343.54	G	

Table 16-3 – Doble Bushing Test Results (2007)

Bushing C2

ID	Serial #	NP %PF	NP Cap	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap (pF)	IR_{auto}	IR_{man}
H1	250663		379	2.001	1.606	0.0750	0.47	1.00	425.88	I	
H2	250881		384	2.000	1.613	0.0910	0.56	1.00	427.82	I	
H3	251439		390	2.000	1.643	0.0890	0.54	1.00	435.76	I	
X1	251307		339	2.000	1.432	0.0950	0.66	1.00	379.89	I	
X2	251308		341	2.000	1.434	0.0980	0.68	1.00	380.48	I	
X3	251311		366	2.000	1.535	0.1250	0.81	1.00	407.20	I	

Table 16-4 – Bushing Test Results (2007)

Hot Collar Test

Serial #	ID	Test Mode	Skirt #	Test kV	mA	Watts	IR_{auto}	IR_{man}
251458	Y1	GROUND	1	10.003	0.1170	0.0360	G	
251459	Y2	GROUND	1	10.004	0.1210	0.0370	G	
251457	Y3	GROUND	1	10.003	0.1210	0.0450	G	
251456	N	GROUND	1	10.003	0.1180	0.0790	G	

Table 16-5 – Exciting Current Test Results (2007)

Doble Exciting Current Test

			H1 - H0			H2 - H0			H3 - H0				
DETC	LTC	Test kV	mA	Watts	X	mA	Watts	X	mA	Watts	X	IR_{auto}	IR_{man}
	1	10.018	16.391	160.41	L	10.096	100.62	C	15.702	154.98	L	G	
	5	9.995	17.782	172.67	L	10.996	109.95	C	17.073	167.32	L	G	
	9	10.011	19.436	188.16	L	12.059	120.59	L	18.687	182.66	L	G	
	13	10.011	21.338	205.56	L	13.347	133.12	L	20.553	199.73	L	G	
	17	10.018	23.595	226.91	L	14.837	147.66	L	22.763	220.82	L	G	

6.2. SSD T4 – (CGE 288838)

Doble test was available only for 2012. The overall test and bushings test results for this transformer are shown in **Tables 17** below.

The following is observed:

- The winding power factor value CH is below the allowed limit, but CT is above 0.5%. Please compare to previous results. The negative P.F for CHT is most likely because of the ground shield between the LV winding and the TV winding. **Table 17-1**
- The C1 power factor and capacitance values for HV & LV bushings are all acceptable. IEEE Std C57.19.01-2000 specifies a limit of 0.5% for C1 power factor for oil impregnated paper insulated bushings. ABB recommends that the bushings be replaced whenever the power factor is double the nameplate value. **Table 17-2**
- The measured C2 capacitance for HV & LV bushings is higher than the nameplate values. This needs to be compared to initial benchmark test results. **Table 17-3**
- The hot collar tests for TV bushings and neutral bushing are below recommended limit (0.1 W at 10 kV). **Table 17-4**
- The Doble exciting current test are normal. **Table 17-5**

Table 17-1 – Doble Overall Test Results (2012)

Meas.	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap(pF)	IR_{auto}	IR_{man}
CH + CHT	10.010	121.82	3.893		1.00	32313.1		
CH	10.006	121.09	3.986	0.33	1.00	32119.9	G	
CHT(UST)	10.005	0.7240	-000.07	-0.97	1.00	192.10	I	
CHT		0.730	-0.093	-1.27	1.00	193.200	I	
CT + CHT	5.003	130.06	11.414		1.00	34497.8		
CT	5.002	129.35	11.458	0.89	1.00	34309.3	G	
CHT(UST)	5.003	0.7170	-000.06	-0.84	1.00	190.30	I	
CHT		0.710	-0.044	-0.62	1.00	188.500	I	

Table 17-2 – Doble Bushing Test Results (2012)

Bushing C1

ID	Serial #	NP %PF	NP Cap	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap (pF)	IR_{auto}	IR_{man}
H1	245304	.3	416	10.008	1.554	0.0450	0.29	1.00	412.28	G	
H2	245325	.25	421	10.008	1.575	0.0360	0.23	1.00	417.67	G	
H3	245303	.28	420	10.008	1.578	0.0430	0.27	1.00	418.47	G	
X1	245284	.23	353	10.008	1.305	0.0290	0.22	1.00	346.11	G	
X2	245279	.24	370	10.009	1.398	0.0310	0.22	1.00	370.75	G	
X3	245280	.24	359	10.009	1.367	0.0440	0.32	1.00	362.63	G	

Table 17-3 – Doble Bushing Test Results (2012)

Bushing C2

ID	Serial #	NP %PF	NP Cap	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap (pF)	IR_{auto}	IR_{man}
H1	245304		402	2.000	1.640	0.0540	0.33	1.00	434.90	G	
H2	245325		388	2.000	1.578	0.0520	0.33	1.00	418.49	D	
H3	245303		402	2.001	1.626	0.0550	0.34	1.00	431.23	I	
X1	245284		377	2.000	1.716	0.0900	0.52	1.00	455.10	G	
X2	245279		356	2.000	1.439	0.0470	0.33	1.00	381.61	G	
X3	245280		383	2.000	1.526	0.0450	0.29	1.00	404.71	G	

Table 17-4 – Bushing Test Results (2012)

Hot Collar Test

Serial #	ID	Test Mode	Skirt #	Test kV	mA	Watts	IR_{auto}	IR_{man}
244961	Y1	GROUND	1	10.006	0.1250	0.0740	G	
244966	Y2	GROUND	1	10.006	0.1150	0.0230	G	
244962	Y3	GROUND	1	10.007	0.1160	0.0250	G	
244699	N	GROUND	1	10.007	0.1150	0.0630	G	

Table 17-5 – Exciting Current Test Results (2012)

Doble Exciting Current Test

			H1 - H0			H2 - H0			H3 - H0				
DETC	LTC	Test kV	mA	Watts	X	mA	Watts	X	mA	Watts	X	IR_{auto}	IR_{man}
	1	10.027	14.950	147.67	L	10.418	104.09	L	15.931	152.39	L	G	
	9	10.025	17.799	174.37	L	12.231	121.75	L	19.059	180.30	L	G	
	17	10.035	21.646	210.67	L	15.000	148.47	L	23.184	218.38	L	G	

6.3. STB T1 – (CGE 288894)

Doble test was available only for 2011. The overall test and bushings test results for this transformer are shown in **Tables 18** below.

The following is observed:

- The winding power factor value CH & CT are below the allowed limit. The negative P.F for CHT is most likely because of the ground shield between the LV winding and the TV winding. **Table 18-1**
- The C1 power factor and capacitance values for HV & LV bushings are all acceptable. IEEE Std C57.19.01-2000 specifies a limit of 0.5% for C1 power factor for oil impregnated paper insulated bushings. ABB recommends that the bushings be replaced whenever the power factor is double the nameplate value. **Table 18-2**
- The measured C2 capacitance for HV & LV bushings is higher than the nameplate values. This needs to be compared to initial benchmark test results. **Table 18-3**
- The hot collar tests for TV bushings and neutral bushing are below recommended limit (0.1 W at 10 kV). **Table 18-4**
- The Doble exciting current test are normal. **Table 18-5**

Table 18-1 – Doble Overall Test Results (2011)

Meas.	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap(pF)	IR_{auto}	IR_{man}
CH + CHT	10.008	122.45	3.944		1.00	32481.4		
CH	10.005	121.72	4.017	0.33	1.00	32287.1	G	
CHT(UST)	10.005	0.7200	-000.08	-1.11	1.00	190.92	I	
CHT		0.730	-0.073	-1.00	1.00	194.300	I	
CT + CHT	4.001	129.24	4.660		1.00	34280.1		
CT	4.001	128.52	4.634	0.36	1.00	34090.1	G	
CHT(UST)	4.002	0.7160	0.0060	0.08	1.00	189.87	I	
CHT		0.720	0.026	0.36	1.00	190.000	I	

Table 18-2 – Doble Bushing Test Results (2011)

Bushing C1

ID	Serial	NP %PF	NP Cap	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap(pF)	IR_{auto}	IR_{man}
H3	247915	.24	417	10.008	1.544	0.0350	0.23	1.00	409.52	G	
X1	246782	.27	353	10.008	1.317	0.0280	0.21	1.00	349.37	G	
X2	246784	.27	353	10.008	1.321	0.0280	0.21	1.00	350.33	G	
X3	246618	.27	352	10.008	1.324	0.0280	0.21	1.00	351.12	G	
H2	248124	.26	415	10.008	1.536	0.0350	0.23	1.00	407.34	G	
H1	246741	.28	409	10.008	1.513	0.0420	0.28	1.00	401.26	G	

Table 18-3 – Doble Bushing Test Results (2011)

Bushing C2

ID	Serial #	NP %PF	NP Cap	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap(pF)	IR_{auto}	IR_{man}
H1	246741		391	2.001	1.649	0.0640	0.39	1.00	437.49	G	
H2	248124		392	2.000	1.637	0.0640	0.39	1.00	434.34	G	
H3	247915		387	2.001	1.651	0.0690	0.42	1.00	437.87	G	
X1	246782		359	2.000	1.440	0.0390	0.27	1.00	382.06	G	
X2	246784		355	2.001	1.413	0.0390	0.28	1.00	374.81	G	
X3	246618		354	2.000	1.403	0.0380	0.27	1.00	372.23	G	

Table 18-4 – Bushing Test Results (2011)

Hot Collar Test

Serial #	ID	Test Mode	Skirt #	Test kV	mA	Watts	IR_{auto}	IR_{man}
248098	Y1	GROUND	1	10.010	0.1020	0.0220	G	
248096	Y2	GROUND	1	10.009	0.1000	0.0270	G	
248097	Y3	GROUND	1	10.009	0.1030	0.0220	G	
248095	N	GROUND	1	10.006	0.1020	0.0240	G	

Table 18-5 – Exciting Current Test Results (2011)

Doble Exciting Current Test

			H1 - H0			H2 - H0			H3 - H0				
DETC	LTC	Test kV	mA	Watts	X	mA	Watts	X	mA	Watts	X	IR_{auto}	IR_{man}
	1	10.034	15.894	158.43	L	10.304	102.76	C	16.452	161.67	L	G	
	9	10.037	18.827	186.57	L	12.392	123.86	L	19.367	188.79	L	G	
	17	10.041	22.755	224.48	L	14.900	148.64	L	23.163	224.70	L	G	

6.4. STB T2 – (CGE 288839)

Doble test was available only for 2008. The overall test and bushings test results for this transformer are shown in **Tables 19** below.

The following is observed:

- The winding power factor value CH & CT are below the allowed limit. The negative P.F for CHT is most likely because of the ground shield between the LV winding and the TV winding. **Table 19-1**
- The C1 power factor and capacitance values for HV & LV bushings are all acceptable. IEEE Std C57.19.01-2000 specifies a limit of 0.5% for C1 power factor for oil impregnated paper insulated bushings. ABB recommends that the bushings be replaced whenever the power factor is double the nameplate value. **Table 19-2**
- The measured C2 capacitance for HV bushings is higher than the nameplate values by more than 10%. This needs to be compared to initial benchmark test results and investigated. The measured C2 capacitance for LV bushings is higher than the nameplate values but within 10%. **Table 19-3**
- The hot collar tests for TV bushings and neutral bushing are below recommended limit (0.1 W at 10 kV). **Table 19-4**
- The Doble exciting current test are normal. **Table 19-5**

Table 19-1 – Doble Overall Test Results (2008)

Meas.	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap(pF)	IR_{auto}	IR_{man}
CH + CHT	10.011	122.14	3.635	0.26	0.88	32399.5		
CH	10.004	121.38	3.650	0.26	0.88	32197.8	G	
CHT(UST)	10.003	0.7200	-000.01	-0.12	0.88	191.08	I	
CHT		0.760	-0.015	-0.18	0.88	201.700	I	
CT + CHT	4.001	132.53	4.722	0.32	0.88	35153.3		
CT	4.001	131.80	4.739	0.32	0.88	34961.5	G	
CHT(UST)	4.001	0.7180	-000.01	-0.12	0.88	190.36	I	
CHT		0.730	-0.017	-0.20	0.88	191.800	I	

Table 19-2 – Doble Bushing Test Results (2008)

Bushing C1

ID	Serial	NP %PF	NP Cap	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap(pF)	IR_{auto}	IR_{man}
H1	246350	.25	411	10.005	1.525	0.0330	0.21	0.96	404.45	G	
H2	246448	.28	433	10.005	1.611	0.0400	0.24	0.96	427.33	G	
H3	246447	.28	434	10.005	1.620	0.0420	0.25	0.96	429.61	G	
X1	245184	.26	369	10.005	1.386	0.0330	0.23	0.96	367.76	G	
X2	243251	.24	376	10.005	1.403	0.0330	0.23	0.96	372.10	G	
X3	246347	.25	352	10.004	1.322	0.0280	0.20	0.96	350.72	G	

Table 19-3 – Doble Bushing Test Results (2008)

Bushing C2

ID	Serial	NP %PF	NP Cap	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap(pF)	IR_{auto}	IR_{man}
H1	246350		400	2.000	1.701	0.0850	0.50	1.00	451.28	I	
H2	246448		379	2.000	1.608	0.0730	0.45	1.00	426.63	I	
H3	246447		381	2.000	1.602	0.0760	0.47	1.00	424.85	I	
X1	245184		346	2.000	1.404	0.0500	0.36	1.00	372.34	D	
X2	243251		345	2.000	1.422	0.0540	0.38	1.00	377.08	D	
X3	246347		374	2.000	1.501	0.0500	0.33	1.00	398.04	D	

Table 19-4 – Bushing Test Results (2008)

Hot Collar Test

Term ID	ID	Test Mode	Skirt #	Test kV	mA	Watts	IR_{auto}	IR_{man}
244967	Y1	GROUND	1	10.003	0.1160	0.0240	G	
244953	Y2	GROUND	1	10.003	0.1160	0.0240	G	
244959	Y3	GROUND	1	10.003	0.1180	0.0260	G	
244964	N	GROUND	1	10.003	0.1140	0.0260	G	

Table 19-5 – Exciting Current Test Results (2008)

Doble Exciting Current Test

			H1 - H0			H2 - H0			H3 - H0				
DETC	LTC	Test kV	mA	Watts	X	mA	Watts	X	mA	Watts	X	IR_{auto}	IR_{man}
	1	10.017	15.471	153.74	L	9.875	98.173	C	15.410	151.83	L	G	
	9	10.010	18.174	179.19	L	11.737	117.36	C	18.256	178.57	L	G	
	17	10.016	22.002	215.40	L	14.332	142.83	L	22.102	214.90	L	G	

7. Maintenance History

7.1. SSD T1 – (CGE 289147)

Electrical testing was performed in this transformer on 2007. The tests included winding resistance, insulation resistance and polarization index test. The test results are shown in **Table 20** below.

- The winding resistance test for HV winding is consistent between phases, however the measured resistance is much lower than the other results for the sister units.
- The winding resistance tests for LV & TV windings are consistent between phases, and also very close to the other sister units.
- The ratio test and core Megger test was not performed.
- The insulation resistance test was performed and results look normal in G-ohms, however the polarization index is lower than the ABB suggested value of 2.0 for HV/LV to ground.

Table 20-1 – Insulation Resistance and Polarization Index Test Results

Test Date: 2007/09/05	Test Completed By: GH.	J.D.E. W/O #:	
Y - HL Grounded	1 min - 1.84	10 min 5.95	3.18 %
[illegible]	1 min	10 min	
~~[illegible]~~	1 Min. Mega Ω	10 Min. Mega Ω	Index. %
HL-G Y Grounded Tert. - Grounded	1 Min. 2.28 Mega Ω	10 Min. 3.46 Mega Ω	Index. 1.52 %
CORE GROUND: (500 Volt test)			
Externally Connected Yes ____ No ____			
RESISTOR: (Ohms)		CORE GROUND: (Mega Ohms)	

Table 20-2 – Winding Resistance Test Results

TAP POSITION	WINDING TESTED	CURRENT RANGE	RESISTANCE RANGE	% CURRENT	RESISTANCE	RESISTANCE DELTA x 1.5
Found 6	6 Ø A	500mA	2	106.6%	.405	
Found 6	6 Ø B	500mA	2	106.5%	.442	
Found 6	6 Ø C	500mA	2	106.6%	.412	
Max. Raise 17	Ø A	500mA	2	106.4	.485.	
Max. Raise 17	Ø B	500 mA	2	106.5 %	.461	
Max. Raise 17	Ø C	500mA	2	x 106.5%	.464	
Max. Lower 1	Ø A	500mA	2	x 106.4%	.452	
Max. Lower 1	Ø B	500mA	2	106.4%	.458	
Max. Lower 1	Ø C	500 mA	2	106.4%	.458	
Left 6	Ø A	500mA	2	106.5%	.407	
Left 6	Ø B	500mA	2	106.4 %	.437	
Left 6	Ø C	500mA	2	x 106.5%	.407	
Non Tap Winding	Ø A.	500 mA	2	104 %	.570	
Non Tap Winding	Ø B	500mA	2	104.1%	.577	
Non Tap Winding	Ø C	500mA	2	104.1%	.570	
Tertiary Winding	Ø. A B A gnd	500mA	200m	107.2	5.7	
Tertiary Winding	Ø B C B gnd	500 mA	200m	107.2	5.5	
Tertiary Winding	Ø A C A gnd	500 mA	200m	107.2	5.3	

Note: Observe Indicator Light & Record OHMS or MILLI-OHMS

7.2. SSD T4 – (CGE 288838)

Electrical testing was performed in 2012 including winding resistance, insulation resistance and polarization index test. The test results are shown in **Table 21** below.

- The winding resistance test for HV & LV & TV windings is consistent between phases.
- The ratio test was not performed.
- The core Megger test was performed and result looks normal.
- The insulation resistance test was performed and results look normal in G-ohms however the polarization index is lower than the ABB suggested value of 2.0.

Table 21-1 – Insulation Resistance and Polarization Index Test Results

CORE GROUND: (500 Volt test)				
Externally Connected Yes ___ No ✓				
RESISTOR: (Ohms)	1min	10 mi	CORE GROUND: (Mega Ohms) 780 mega Ω	
Auto XFmer H-Grn.	3.16 gΩ	4.44 gΩ	1.14 pi	
L-Grn.	3.60 gΩ	5.00 gΩ	1.39 pi	Sheet 2 of 3
HL-Grn	3.82 gΩ	5.25 gΩ	1.37 pi	

Table 21-2 – Winding Resistance Test Results

TAP POSITION	WINDING TESTED	CURRENT RANGE	RESISTANCE RANGE	% CURRENT	RESISTANCE	RESISTANCE DELTA x 1.5
Found 4	H1 – H0	500mA	2 Ω	105.3%	1.023	
Found 4	H2 – H0	500mA	2 Ω	105.3 %	1.018 Ω	
Found 4	H3 – H0	500mA	2 Ω	105.3 %	1.018	
Max. Raise 17	H1 – H0	500mA	2 Ω	105.3 %	1.083	
Max. Raise 17	H2 – H0	500mA	2 Ω	105.3%	1.054	
Max. Raise 17	H3 – H0	500mA	2 Ω	105.4 %	1.052	
Max. Lower 1	H1 – H0	500mA	2 Ω	105.4 %	1.053	
Max. Lower 1	H2 – H0	500mA	2 Ω	105.4 %	1.049	
Max. Lower 1	H3 – H0	500mA	2 Ω	105.4 %	1.046	
Left 4	H1 – H0	500 mA	2 Ω	105.4%	1.023	
Left 4	H2 – H0	500 mA	2 Ω	105.4 %	1.019	
Left 4	H3 – H0	500 mA	2 Ω	105.4%	1.018	
Non Tap Winding	X0 – X1	500 mA	2 Ω	106.3	.592	
Non Tap Winding	X0 – X2	500 mA	2 Ω	106.3	.590 Ω	
Non Tap Winding	X0 – X3	500 mA	2 Ω	106.3	.589 Ω	
Tertiary Winding	Y1 – Y2	5A	200 m	99.9 %	5.4 mΩ	
Tertiary Winding	Y1 – Y3	5A	200 m	99.9 %	5.6 mΩ	
Tertiary Winding	Y2 – Y3	5A	200 m	100.0%	5.6 mΩ	

7.3. STB T1 – (CGE 288894)

Electrical testing was performed in 2011 including winding resistance, insulation resistance and polarization index test. The test results are shown in **Table 22** below.

- The winding resistance test for HV & LV windings is consistent between phases.
- The deviation of the TV winding resistance between phases is 20%. It is recommended to repeat the TV windings resistance test and compare to the sister units.
- The ratio test was not performed.
- The core Megger test was performed and result looks normal.
- The insulation resistance test was performed and results look normal in G-ohms however the polarization index is lower than the ABB suggested value of 2.0 for HV to ground.

The tap changer inspection was performed on September 23rd, 2011 by GE, the following are found: Both two defects were corrected.

- One end of a resistor was misplaced and came into contact with another resistor.
- A loss bolt was found on resistor.

Other findings:

- One bearing in one of second stage fan motors was found to be broken.

Table 22-1 – Insulation Resistance and Polarization Index Test Results

DIELECTRIC ABSORBTION (5 KV): 10 MIN. ÷ 1 MIN. = INDEX			
HL - TG	1 Min. 4.08 Mega Ω	10 Min. 5.85	Index. 1.44 %
T - HLG	1 Min. 3.18 Mega Ω	10 Min. 13.8	Index. 4.34 %
HLT - G	1 Min. 2.04 Mega Ω	10 Min. 4.5	Index. 2.22 %

CORE GROUND: (500 Volt test)	
Externally Connected Yes ✓ No ____	
RESISTOR: (Ohms) N/A	CORE GROUND: (Mega Ohms) > 999

Table 22-2 – Winding Resistance Test Results

TAP POSITION	WINDING TESTED	CURRENT RANGE	RESISTANCE RANGE	% CURRENT	RESISTANCE	RESISTANCE DELTA x 1.5
Found 1	H_1 - H0	500 MA	2 Ω	105.1	1.035	
Found 1	H_2 - H0	500 MA	2 Ω	104.8	1.036	
Found 1	H_3 - H0	500 ma	2 Ω	105.0	1.031	
Max. Raise 9	H_1 - H0	500 ma	2 Ω	105.3	0.948	
Max. Raise 9	H_2 - H0	500 ma	2 Ω	105.3	0.952	
Max. Raise 9	H_3 - H0	500 ma	2 Ω	105.3	0.952	
Max. Lower 1	H1 - H0	500 ma	2 Ω	105.2	1.035	
Max. Lower 1	H2 - H0	500 ma	2 Ω	105.1	1.034	
Max. Lower 1	H3 - H0	500 ma	2 Ω	105.2	1.035	
Left 1						
Left 1						
Left 1						
Non Tap Winding	X_1 - X0	500 ma	2 Ω	105.9	0.582	
Non Tap Winding	X_2 - X0	500 ma	2 Ω	105.9	0.582	
Non Tap Winding	X_3 - X0	500 ma	2 Ω	105.9	0.582	
Tertiary Winding	Y1 - Y2	500 ma	2 Ω	104.6	0.005	0.0075
Tertiary Winding	Y2 - Y3	500 ma	2 Ω	104.3	0.006	0.009
Tertiary Winding	Y1 - Y3	500 ma	2 Ω	104.4	0.006	0.009

7.4. STB T2 – (CGE 288839)

The maintenance test history is not available for this unit.

8. Inspection (SSD T1)

The unit was inspected on January 21, 2014. Entry to the unit was made from the manhole located on the top cover between H2 and H3 bushings. Most of the other man holes and hand holes in the unit were opened also for inspection. It was possible to see and inspect all the active part components.

8.1. Findings and Observations

- Because of risk of broken bushing porcelain falling; H3 and L2 bushing were removed before the inspection. L1 bushing was removed during the inspection.
- Transformer cover was ripped open at the LV side. All the bolts on the LV side and some on the short sides were broken. **See Photos 1&2&3&4**
- All transformer bushings are damaged. The most damaged are the H1, L2 and TV bushings. **See Photos 5&6&7&8**
- The tap changer diverter cylinders of Phases 1 and 3 were separated from their aluminum flanges at the cover. This caused the tap changer assemblies, diverter and selector, to fall. The assemblies were found sitting at the bottom of the tap changer's pocket. No signs of flashover were seen at the selector switches or tap cables. **See Photos 9&10&11&12**
- No indication was found that the fault originated in the tap changers compartment.
- The fire left indications of burning on the tank wall to a level about a foot above the windings. **See Photo 13**
- No signs of flash over were seen in the cleats and leads including tap leads.
- All windings looked good with no signs of failure within the windings. **See Photos 14&15**
- The L1 & L3 bushing's porcelain inside the transformer were shattered. Also marks of flashover were seen on core clamp just opposite to Phase 1 LV bushing. **See Photos 16&17&18**
- No signs of phase to phase failure in the windings were found.
- Each of the LV bushings in this transformer has two leads connected to them. One lead is connected to the winding and the other to the tap changer. **See Sketch 1**
- For Phases 1 and 2 the leads connecting the LV bushings to the windings are disconnected. It seems the two leads were mechanically pulled and cut at the crimp during the fault when the cover opened up. The insulation of the leads looks intact with no signs of failure. **See Photos 19&20&21&22**
- Spitting and melting cooper were seen on the LV windings conductor copper strands of phase one. **See Photo 23**

Photo 1 – Cover Open & Broken Bolts

Photo 2 – Cover Open & Broken Bolts

Photo 3 – Cover Open & Broken Bolts

Photo 4 – Cover Open & Broken Bolts

Photo 5 – LV2 Bushing

Photo 6 – LV2 Bushing

Photo 7 – **LV2 Bushing Porcelain**

Photo 8 – **HV1 Bushing Porcelain**

Photo 9 – LTC Compartment (Phases 2 & 3)

Photo 10 – LTC Compartment (Phases 2 & 3)

Photo 11 – LTC Compartment (Phase 3)

Photo 12 – LTC Compartment (Phases 2 & 1)

Photo 13 – Fire Line on Tank Wall & Core Clamp

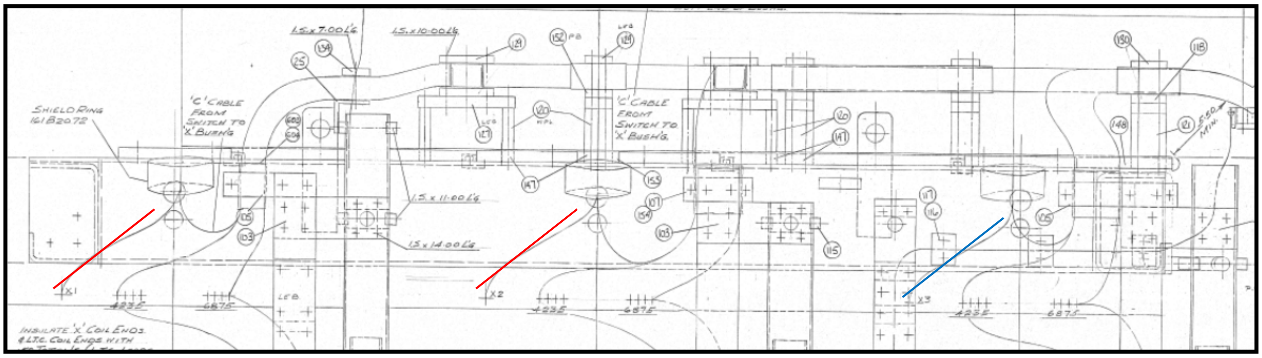
Photo 14 – Windings

Photo 15 – Windings

Photo 16 – LV1 Bushing & Flashover marks

Photo 17 – LV1 Bushing

Photo 18 – LV3 Bushing



Sketch 1: LV bushings Connected to the Windings & Tap Changers

Photo 19 – LV2 Winding Lead Broken

Photo 20 – LV2 Bushing Lead Broken at the Crimp

Photo 21 – LV1 Winding Lead Broken

Photo 22 – LV1 Bushing Lead Broken at the Crimp

Photo 23 – LV1 Winding Conductor Strand Copper Spitting

9. System Analysis during Fault

The system fault data was reviewed by an ABB power system expert and below are the comments:

- Between 9:03:21 and 9:04:49 something occurred causing the MVAR difference between T1 & T4. Most probably T1 transformer was providing (compensating) the MVAR while there was a fault in T4. Detailed data for this time window is not available.
- There is no indication that a system disturbance caused the failure, however we do not have detailed data to for the time before 9:04:57.
- There is no indication that the failure was initiated externally.
- There is no indication that there was a phase to phase failure.

10. Conclusions

A comprehensive short circuit and dielectric study of the design was performed for transformer SN 289147 that was manufactured in 1978 and failed in service in 2014. A review of maintenance data and DGA history was completed. A failure investigation and inspection was also performed.

The short circuit design study showed that the HV and LV windings are able to withstand short circuit forces while the TV winding end rings are not strong enough to withstand the short circuit forces.

The Dielectric study showed that all windings and cable clearances are within the acceptable design levels for the voltage stresses in this transformer.

The DGA, oil quality, transformer power factor and maintenance history of the four transformers were reviewed.

For SSD T1 – CGE 288147

The DGA results showed that:

- The concentration of Acetylene (C2H2) has been above IEEE C57.104-2008 guide condition level 1 (2 ppm) since 1991, The level went up and down since then but was almost stable around the 10ppm. This could be oil leaking from the LTC diverter compartment.
- The oil samples from this transformer have consistently shown high oxygen concentrations.

The oil physical results showed that: (Main tank)

- The interfacial tension values are around 28.0 dynes/cm2 which are below the 32 dynes/cm2 limit recommended by IEEE C57.106-2002 for ≥ 230kV transformers.

The oil physical results showed that: (LTC tank)

- The measured breakdown voltage (around 22.0 kV/mm for LTC-A,B,C) is below the minimum requirement (28 kV/mm for 1 mm gap and 45 kV/mm for 2 mm gap) as outlined by IEEE C57.106-2002.
- The oil samples taken from the LTC-A tank does show moisture content of more than 25 ppm.

The power factor measurements showed that:

- The winding power factor values (CH & CT) are below 0.5%.
- The C1 power factor and capacitance values for HV & LV bushings are all acceptable.
- The measured C2 capacitance for HV & LV bushings is higher than the nameplate values by more than 10%.
- The hot collar tests for TV bushings and neutral bushing are below recommended limit.
- The Doble exciting current test are normal.

The maintenance history showed that:

- The winding resistance test for HV winding is consistent between phases, however the measured resistance is much lower than the other sister units.
- The winding resistance tests for LV & TV windings are consistent between phases, and also very close to the other sister units.
- The insulation resistance test was performed and results look normal in G-ohms, however the polarization index is lower than the ABB suggested value of 2.0 for HV/LV to ground.

For SSD T4 – CGE 288838

The DGA results showed that:

- The concentration of Acetylene (C2H2) has been above IEEE C57.104-2008 guide condition level 1 (2 ppm) since 1991, The level went up and down since then but was almost stable around the 5ppm. This could be oil leaking from the LTC diverter compartment.
- The oil samples from this transformer have consistently shown high oxygen concentrations.

The oil physical results showed that: (Main tank)

- The latest measured breakdown voltage (52.0kV/mm) is above the minimum requirement (30kV/mm) as outlined by Doble Engineering for 230kV transformers.
- The interfacial tension values are around 33.6 dynes/cm2 which is slightly above the 32 dynes/cm2 limit recommended by IEEE C57.106-2002 for 230kV transformers. Lower values may indicate oil soluble contaminants and oxidation products in oil.
- The measured Acid Numbers for the oil samples are all below the recommended limits.
- The measured power factor values at 25/100°C are all below the suggested limits.
- The moisture in oil is within the acceptable limits.

The oil physical results showed that: (LTC tank)

- The measured breakdown voltage (between 20.0 kV/mm and 21.0 kV/mm for LTC-A,B,C) is below the minimum requirement (28 kV/mm for 1 mm gap and 45 kV/mm for 2 mm gap).
- IEEE C57.106-2002 Table 12 recommends that the maximum limit of water content in oil for LTC is not to exceed 25 ppm. The oil samples taken from the LTC tank show moisture content much less than 25 ppm.

The power factor measurements showed that:

- The winding power factor value CH is below the allowed limit, but CT is above 0.5%.
- The C1 power factor and capacitance values for HV & LV bushings are all acceptable.
- The measured C2 capacitance for HV & LV bushings is higher than the nameplate values. This needs to be compared to initial benchmark test results.
- The hot collar tests for TV bushings and neutral bushing are below recommended limit.
- The Doble exciting current test are normal.

The maintenance history showed that:

- The winding resistance test for HV & LV & TV windings is consistent between phases.
- The ratio test was not performed.
- The core Megger test was performed and result looks normal.
- The insulation resistance test was performed and results look normal in G-ohms however the polarization index is lower than the ABB suggested value of 2.0.

For STB T1 – CGE 288894

The DGA results showed that:

- The concentration of Acetylene (C2H2) has been below IEEE C57.104-2008 guide condition level 1 (2 ppm) since 2009. However the DGA sample for the year 1979 shows high level of C2H2. This could be a bad oil sample.
- The oil samples from this transformer have consistently shown high oxygen concentrations.

The oil physical results showed that: (Main tank)

- The latest measured breakdown voltage (62.0kV/mm) is above the minimum requirement (50kV/mm) as outlined in IEEE C57.106-2002 for 230kV transformers with service aged insulating oil based on D1816-2mm method.

- The interfacial tension values are around 30.4 dynes/cm2 which is below the suggested limits (32 dynes/cm2) recommended by IEEE C57.106-2002 for 230kV transformers. Lower values may indicate oil soluble contaminants and oxidation products in oil.
- The measured Acid Numbers for the oil samples are all below the recommended limits.
- The measured power factor values at 25/100°C are all below the suggested limits.
- The moisture in oil is within the acceptable limits.

The oil physical results showed that: (LTC tank)

- The latest measured breakdown voltage is 30, 31 and 33 kV/mm for LTC-A,B,C. the suggested limits is 28 kV/mm for 1 mm gap and 45 kV/mm for 2 mm gap as outlined by IEEE C57.106-2002.
- IEEE C57.106-2002 Table 12 recommends that the maximum limit of water content in oil for LTC is not to exceed 25 ppm. The latest oil samples taken from the LTC tank show moisture content of less than 25 ppm.

The power factor measurements showed that:

- The winding power factor value CH & CT are below the allowed limit.
- The C1 power factor and capacitance values for HV & LV bushings are all acceptable.
- The measured C2 capacitance for HV & LV bushings is higher than the nameplate values. This needs to be compared to initial benchmark test results.
- The hot collar tests for TV bushings and neutral bushing are below recommended limit
- The Doble exciting current test are normal.

The maintenance history showed that:

- The winding resistance test for HV & LV windings is consistent between phases.
- The deviation of the TV winding resistance between phases is 20%.
- The ratio test was not performed.
- The core Megger test was performed and result looks normal.
- The insulation resistance test was performed and results look normal in G-ohms however the polarization index is lower than the ABB suggested value of 2.0 for HV to ground.

For STB T2 – CGE 288839

The DGA results showed that:

- The transformer has consistently shown very high concentrations (>20 ppm) of Acetylene (C2H2) since 1986, which is far above the IEEE C57.104-2008 guide condition level 1 (2 ppm). The high concentration of C2H2 indicates that possible high energy arcing occurred somewhere inside the transformer. The other reason could be oil leaking from the LTC diverter compartment. The Acetylene levels are about 10ppm for few years now. This needs to be monitored closely. Any sudden increase of Acetylene needs to be investigated.
- The oil samples from this transformer have consistently shown high oxygen concentrations

The oil physical results showed that: (Main tank)

- The latest measured breakdown voltage (68.0kV/mm) is above the minimum requirement (50kV/mm) as outlined in IEEE C57.106-2002 for 230kV transformers with service aged insulating oil based on D1816-2mm method.
- The interfacial tension values are around 28.7 dynes/cm2 which is below the suggested limits (32 dynes/cm2) recommended by IEEE C57.106-2002 for 230kV transformers.
- The measured Acid Numbers for the oil samples are all below the recommended.
- The measured power factor values at 25/100°C are all below the suggested limits.
- The moisture in oil is within the acceptable limit.

The oil physical results showed that: (LTC tank)

- The latest measured breakdown voltage is 17, 21 and 23 kV/mm for LTC-A,B,C, which is below the suggested minimum limits (28 kV/mm for 1 mm gap and 45 kV/mm for 2 mm gap).
- IEEE C57.106-2002 Table 12 recommends that the maximum limit of water content in oil for LTC is not to exceed 25 ppm. The latest oil samples taken from the LTC tank show moisture content of more than 25 ppm for all three LTCs.

The power factor measurements showed that:

- The winding power factor value CH & CT are below the allowed limit.
- The C1 power factor and capacitance values for HV & LV bushings are all acceptable.
- The measured C2 capacitance for HV bushings is higher than the nameplate values by more than 10%. <u>This needs to be compared to initial benchmark test results and investigated.</u> The measured C2 capacitance for LV bushings is higher than the nameplate values but within 10%.
- The hot collar tests for TV bushings and neutral bushing are below recommended limit.
- The Doble exciting current test are normal.

The failure inspection of SSD T1 showed the following:

- All transformer bushings are damaged.
- The tap changer diverter cylinders of Phases 1 and 3 were separated from their aluminum flanges at the cover.
- There was no indication that the fault originated in the tap changers compartment.
- No signs of flash over were seen in the cleats and leads including tap leads.
- All windings looked good with no signs of failure within the windings. It was not possible however to see the internal windings.
- No sign of phase to phase failure in the windings was found during the inspection.
- The L1 & L3 bushing's porcelain inside the transformer were shattered. Also marks of flashover were seen on core clamp just opposite to Phase 1 LV bushing.
- For Phases 1 and 2 the leads connecting the LV bushings to the windings are disconnected. It seems the two leads were mechanically pulled and cut at the crimp during the fault when the cover opened up. The insulation of the leads looks intact with no signs of failure.
- Spitting and melting copper were seen on the LV windings conductor copper strands of phase one.

The system analysis during the fault showed that:

- Between 9:03:21 and 9:04:49 something happened causing the MVAR difference between T1 & T4. Most probably T1 transformer was providing (compensating) the MVAR while there was a fault in T4.
- There is no indication that a system disturbance caused the failure.
- There is no indication that the failure was initiated externally.
- There is no indication that there was a phase to phase failure.

Based on the internal inspection observations, all the information available and the system analysis findings, it is concluded that most probably the LV1 or LV2 bushing failed first which initiated the failure and resulting fire.

11. Recommendations

The following is recommended during dismantling/scraping of the failed unit:

- Inspect closely the LTC diverter switches.
- As there was lots of carbon, debris, oil and water inside the tank during the internal inspection, closer inspection of the windings after un-tanking the active part is recommended.

The following is recommended for the other three transformers:

- Comprehensive DGA, oil quality tests and transformer testing is to be planned.
- Any bushings with high C2 capacitance need to be compared to initial benchmark test results. Higher results need to be investigated.
- As the bushings of these transformers are about forty years old, it is recommended to replace the bushings.
- Add a conservator diaphragm.
- Consider adding oxidation inhibitor to oil.
- Monitor Acetylene (C_2H_2) closely especially for (STB T2).
- Confirm that the cause of the acetylene is due to seeping from the LTC diverter oil compartment. This can be done by applying pressure on the diverter compartment and checking if oil leaks into the main compartment (the pressure drops).
- Consider adding online gas monitor.
- Consider adding bushing monitors.
- Measure the oil break down voltage per ASTM D1816 (1mm or 2mm) method.
- Repeat the TV windings resistance test (on unit STB T1) and compare to the sister unit results.
- Repeat the HV resistance test (on unit SSD T1) and compare to the sister unit results.
- Inspect and overhaul the LTC diverters. Most LTC manufacturers recommend LTC diverter inspections every 7 years. It is also recommended to re-condition or replace the oil in the LTC diverter tanks with new oil if it is not already done.

120 DAY - POWER TRANSFORMER INSPECTION

Station: SSDTS Date: 2013/10/26 Readings By: WP/DA

WEATHER CONDITIONS: dry: ☐ rain: ☐ humidity: ☐ ambient temperature: ________ ^{0}C

NOTE: All ITEMS MUST BE COMPLETED OR MARKED N/A (unless otherwise Instructed).

Visual Inspection:

- > Primary terminations
- > Tank & fittings
- > Explosion vent
- > Check for gas accumulation
- > Paint conditions
- > Temperatures (Current & Peak)
- > Check bushings
- > Access ladder/guard
- > Foundation
- > Silica Gel Breather checked
- > Oil Levels (Normal, High, Low)
- ➢ Rust Condition
  - A - Minor
  - B - Moderate
  - C – Severe
- ➢ **Check Concrete Base**
- > Check &Report all Oil leaks As per EERP (Environmental Emergency Response Plan)

Operate Manually:

- > Cabinet heater thermostat
- > Fan controls
- > Circulating Pumps controls (T1, T2, T3) HRDTS

Trf. No. T4 **Tap Pos.** 5
Load: M.W. ________ **(or) Amps** ________
Temp: Winding 35 **/Peak** 50 **Oil:** 30 **/Peak** 50
Oil Levels: Tank ✓ **Tap Chr.** ✓ **Bush.** ✓
SF$_6$ Bushing Diff. (kPa): H1 X **H2** X **H3** X
Fan Load Current (amps): Stage I 2.9 **Stage II** 1.4
Fan Control Return to Auto/Remote ________
Cabinet Heaters: On ✓ **Off** ________ **Amps** 1.1
Tap Chr: Counter 010270
Rust Condition: Tank ✓ **Cont.Cabinet** ✓ **Rads** ✓
Silica Gel: OK ✓ **Replace if 50% or Greater Contamination:** ___
Explosion Vent Diaphragm OK
Remarks: ________

Trf. No. T1 **Tap Pos.** 5
Load: M.W. ________ **(or) Amps** ________
Temp: Winding 25 **/Peak** ________ **Oil:** 45 **/Peak** 50
Oil Levels: Tank ✓ **Tap Chr.** ✓ **Bush.** ✓
SF$_6$ Bushing Diff. (kPa): H1 ____ **H2** ____ **H3** ____
Fan Load Current (amps): Stage I 27.6 **Stage II** 9.4
Fan Control Return to Auto/Remote ✓
Cabinet Heaters: On ✓ **Off** ________ **Amps** 1.2
Tap Chr: Counter 43145
Rust Condition: Tank ✓ **Cont.Cabinet** ✓ **Rads** ✓
Silica Gel: OK___ **Replace if 50% or Greater Contamination:** ___
Explosion Vent Diaphragm OK
Remarks: ________

Trf. No. ________ **Tap Pos.** ________
Load: M.W. ________ **(or) Amps** ________
Temp: Winding ____ **/Peak** ____ **Oil:** ____ **/Peak** ____
Oil Levels: Tank ____ **Tap Chr.** ____ **Bush.** ____
SF$_6$ Bushing Diff. (kPa): H1 ____ **H2** ____ **H3** ____
Fan Load Current (amps): Stage I ____ **Stage II** ____
Fan Control Return to Auto/Remote ________
Cabinet Heaters: On ____ **Off** ____ **Amps** ____
Tap Chr: Counter ________
Rust Condition: Tank ____ **Cont.Cabinet** ____ **Rads** ____
Silica Gel: OK___ **Replace if 50% or Greater Contamination:** ___
Explosion Vent Diaphragm ________
Remarks: ________