Arizona Public Service
Westwing Substation Autotransformer
Failure Analysis Report

Submitted By
James B. Templeton
Harold Moore & Associates, Inc.
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1. Introduction

This report covers the investigation of the autotransformer failures at the APS Westwing Substation. This failure involved the autotransformers in two of the banks, T1 and T4, with damage to five autotransformers. The transformers involved were all three units in the T1 bank (T733, T732, and T731), the spare transformer for T1 and T4 banks, and T790 in the T4 bank. This was a major failure by any measure with the destruction of this many large autotransformers. Thus, it is appropriate to investigate the event in great detail to develop a most probable cause of the failure

The failure investigation process includes several steps. The areas of review include system events, historical data and maintenance data, operating data, and physical inspection of the transformer involved in the failure event. The information will be combined and correlated as a body of knowledge that fits together technically to explain the event. The methodology will include theoretical calculations, laboratory analyses, and empirical analyses.

2. Transformer Description

The affected autotransformers in Banks T1 and T4 were purchased from the Westinghouse Electric Corporation in the early 1970's. The transformers were designed and manufactured at the Westinghouse Muncie, Indiana facility. This facility was sold to ABB in 1990 and it was through ABB that the original design information was obtained.

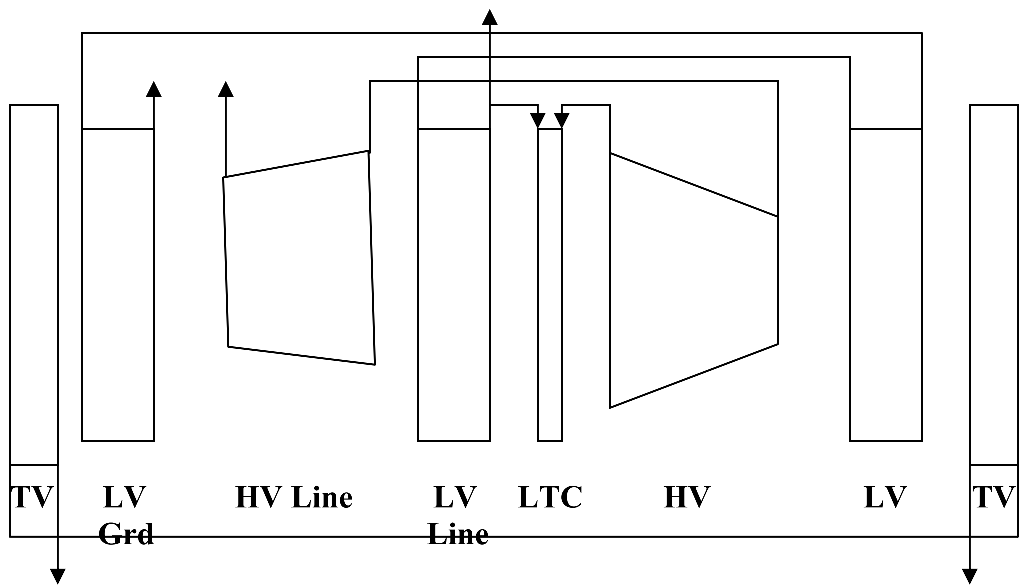
This transformer is a single-phase shell form design with the following ratings:

HV: 500 kV, ±10% LTC, 1425 kV BIL, 200/266.7/333.3 MVA, 55°C
LV: 230 kV, 825 kV BIL, 200/266.7/333.3 MVA, 55°C
TV: 35.5 kV, 200 kV BIL, 43.8/53.1/73.0 MVA, 55°C

Although the rating shown above is for 55°C rating, the unit has actually been operated as a 65°C rise unit. This rating is inherent with the design since the transformer was manufactured with thermally upgraded insulation. Throughout the analysis of this failure event, the ratings and currents will be related to the 55°C rating. The calculations are not affected by the actual operating MVA of the transformers versus the rating used for the calculations. The reason for this is that the calculations vary by given ratios based on MVA.

This shell form design is characterized as having a 4 H-L winding arrangement. This is one of the more distinguishing characteristics of the design. The term 4 H-L refers to the number of interleaving spaces between HV and LV winding groups. The 4 H-L configuration is typical for transformers of this voltage and MVA rating. There are 42 coils in the phase and they are distributed in the phase according to the following sketch.

Figure 1



In this sketch the HV line lead connects to the left side of the block labeled as HV line. The various blocks of the HV and LV are connected I series to accomplish the autotransformer connection and the winding blocks are interleaved with 4 gaps between the winding blocks. The TV winding is arranged on the outermost ends of the phase. The LV line is connected to the terminal in the middle LV group, which is labeled as LV Line. The neutral terminal is connected to the terminal of the LV Grd. group. Finally, the TV bushings are connected to the terminals associated with each of the two TV groups. This winding arrangement was typical for an autotransformer at the time this transformer was manufactured. The clearances between coils were also in line with the clearances for the voltage class of these windings.

The number of coils in each of the winding groups was also typical and reasonable for this voltage class. The conductor used in all coils was paper-insulated magnet wire. The paper used for the turn insulation was kraft paper. The copper used was soft, annealed copper. The solid insulation material used for barriers and formed insulation parts was low-density calendered pressboard. Again, these were the typical materials available in the industry at the time of manufacture.

The LTC used in this transformer is a Westinghouse Model UTH. This LTC has not been manufactured for many years, since the late 1970's.

The physical data for this transformer are as follows for the weights:

Copper weight: 40550 lbs
Core weight: 186200 lbs
Insulation weight: 36000 lbs
Bottom tank weight: 28000 lbs
Coil supports: 6500 lbs

Total Core & coil weight: 300000 lbs

Top tank weight: 30000 lbs
LTC weight: 20000 lbs
Radiator weight: 87000 lbs
Oil weight: 150000 lbs

Total Weight: 585000 lbs

The review of the design data provided revealed the design of the transformer was as expected for production from the Muncie facility at the time of manufacture.

3. Failure Event

The failure of the transformers associated with the T1 bank occurred on early July 4, 2004 at 18:59 hours. The failure was not anticipated with any operational data or measurements taken prior to the event. The DFR data indicated the fault initiated in phase 2 of the T1 bank, which was T732. The fault was cleared in approximately 4 cycles.

Of greater importance was the system fault event that occurred on 6/14/04 on the 230 kV Liberty to Westwing line. The system fault affected a large area, but the importance in this investigation is the impact on the autotransformers at the Westwing Substation. Others within APS have documented the details of the system fault and only portion of the details used in this investigation include the fault current magnitude and duration to which the transformers were subjected. Five system faults occurred during the time of the fault initiation at 7:40:55.747 on 6/14/04 and clearing the last fault at 8:32:53.121. Thus, the 5 faults occurred during ~53 minutes on 6/14/04. This is a relatively short period of time for recurring events of this type. APS personnel provided the following information.

All currents are values of the LV line currents, i.e. 230 kV system currents.

Fault #1:
Initiated at 7:40:55.747 as a phase C – N, phase C current = 18060 A
7:41:01.982 fault changed to B – C – N
7:41:08.104 fault changed to A – B – C – N
7:41:18.900 phase A current = 12400 A, phase B = 16750 A, phase C = 15790 A
7:41:34:300 phase A = 4160 A, phase B = 4355 A, phase C = 4118 A
Fault #1 cleared after 38.868 seconds. This fault affected the transformers in T1, T4, and T10 banks. Therefore, the currents above would be divided by three for the current through each bank.

Fault #2:
Fault initiated at 7:54:55.728 as a phase A – B – C – N fault.
7:54:55.835 fault #2 cleared, which is 6.4 cycles in duration. Transformers in T1 not affected.

Fault #3:
Fault initiated at 8:03:59.764 as a phase A – B – C – N fault. The fault duration was only 2.7 cycles. The T1 transformers were not affected.

Fault #4:
Fault initiated at 8:15:05.574 as a phase A – B – C – N fault. The fault duration was 3.5 cycles and did not affect the T1 bank.

Fault #5:
Fault initiated at 8:32:33.375 as a phase A – B – C – N fault. This fault was carried by the T1 bank of transformers only. The phase currents were: phase A = 12390 A, phase B = 13780 A, and phase C = 13320 A. The fault duration was 19.746 seconds.

The last event involving the T1 bank was a long duration fault. The requirement in the ANSI Standard C57.109 would set the acceptable time limit for a fault as 2 seconds. There are two considerations for the transformer relative to the time duration of a fault: mechanical dynamic stress and the temperature rise of the conductor. The limit on conductor temperature has been established as 250°C. The mechanical stress has not been so easily defined. The major objective is to prevent movement of the conductors that lead to permanent deformation of the conductors. In both cases, the industry has agreed the time limit to be 2 seconds. The point to be derived from this discussion is that the time duration of the faults applied to the T1 bank of transformers was long.

An analysis was performed on the currents by APS personnel to compare the time duration with the damage curve in ANSI C57.109, Figure 4 for Category IV transformers. The fault current in phase B was 13789 A and the 1 PU current in the LV line is 1506 A. This implies the fault current is 9.15 PU. When entering the curve at 9.15 PU and 19.746

seconds, the result is above the damage curve. This will be discussed further in this report.

4. Historical Data

The historical data available for this investigation included paper insulation samples and DGA results. Very simply, the DGA results for this transformer were unremarkable whereas the analysis of the paper samples provides some important information. Paper samples were collected from transformers T790, T789, and T788 from the T4 bank. Thirteen samples were taken from the three units for degree of polymerization (DP) tests. The DP values are summarized below.

T790: DP values – 575, 724, 815, 512, and 562
T789: DP values – 345, 528, 648, and 514
T788: DP values – 906, 837, 561, and 559

These values may be compared with the value for new paper, which is 1200. The value that has been considered as the end of life is 200. The majority of the values are indicative of mid life. These data indicate that the insulation still has a significant amount of life available. Although the samples were taken from the T4 bank, one can assume that the units in the T1 bank should be similar as all units were operated approximately the same and the design and materials are equal.

Another aspect of the historical data for these transformers relates to the maintenance performed on the units. APS performed major maintenance on these transformers in the recent past prior to the failure event. The maintenance activities performed were appropriate for transformers of this age. There was no indication from the information provided that the maintenance procedures were anything but adequate. In other words, the replacement of parts and the processing of the units for return to service appeared to be in order.

5. Inspections

Three inspections were performed in the course of this investigation. The first inspection was performed on 8/30/04 and was an internal inspection of units T733 and T732. Transformer T733 is serial #7001940 and T732 is serial #7001941 as established by Westinghouse.

The second inspection was for the detailed disassembly of the T732 and T733. The disassembly took place during the period of 9/22 – 9/29/04. Both transformers were completely dismantled to assess the differences and similarities of damage to the two transformers.

The third inspection was performed on 10/27 and involved transformer T790 from the T4 bank. This transformer was inspected since it was involved with some of the same

6/14/04 system faults as the transformers in the T1 bank. This transformer did not burn and the phase assembly was intact.

5.1 Internal Inspection Of T732 And T733 Before Disassembly

These two units were selected for the inspection since it had appeared they were directly involved with the major fault in the T1 and T4 transformer banks. The following observations were made during this inspection and the observations are documented with photographs in Appendix A.1.

T732 Transformer

The following observations for this transformer are presented in Photos 1 – 14. Each of the photos is provided with a description.

- The upper tank section was bulged outwards on the HV side at the top.
- The bottom tank was bulged outward in all four segments of the tank.
- The bottom tank steel was torn at the corner between segments 2 and 3 along the lifting hook at this corner.
- The tank braces along the length of segments 2 and 4 of the top section were bulged outward.
- The inspection door of the UTH LTC along the side of the compartment was blown open.
- The outermost panel of the LTC was bulged outward. The most outbound inspection panel was deformed outward as well.
- The HV and LV bushings had fallen into the transformer. I was informed that the HV bushings fell inward several days after the failure during the fire.
- The barrier board between the main tank and the LTC compartment was totally gone.
- The attachment frame for the barrier board was deformed along the two vertical side of the frame. The bending of the frame was toward the LTC compartment.
- The winding arrangement is the standard four high-low configuration used by Westinghouse at the time of manufacture.
- The phase is oriented axially from the segment 2 end of the tank toward the segment 4 end. The HV line enters the phase assembly more toward the segment 2 end. The coils associated with the LTC are located near the center of the phase assembly and there is a group of common winding coils to one side and series winding coils to the other side of the LTC coils. The leads to the LTC exit from the top of the phase assembly in the region of the LTC coils.
- The fire had consumed all of the insulating paper on the conductor as well as the sheets of pressboard insulation between coils and between coils and ground. As such one could see all the way to the floor of the tank along both side of the phase assembly. Thus, the core steel along the outside legs of the core and along the ends of the core was visible.

- Conductor deformation was evident in the LTC group and the adjacent common winding and series winding groups. With all of the paper insulation gone it is virtually impossible to tell which coils are associated with each winding group, thus it is necessary to describe location based on approximate position relative to the winding groups.
- The conductor deformation appeared to be along the outside edges of the coils. The areas involved included the top end and the outside edges of the coil legs.
- The LTC tap leads were not positioned in the orderly manner in which they were manufactured. Movement of the leads was apparent.
- The inspection could only be performed from the topside of the coils and one could not get alongside the legs of the coils. Closer inspection of the coil legs will come with the detailed disassembly of the transformer.
- From the top end vantage point there were not arc marks visible to the inside surfaces of the core. In addition, there were no arc marks visible to the inside surfaces of the tank walls.
- There was an area near the bottom end of the HV line portion of the series winding where conductors may be broken. Closer inspection will have to be made during the disassembly operation.
- The LTC compartment was inspected. There are two compartments in the LTC, one for the selector switch and the other for the transfer switch. The two compartments are normally segregated with a barrier board. This barrier board was also gone. There was considerable mechanical damage to the components in the LTC compartment. As with the main tank, all insulating components in the LTC compartment were destroyed by the fire.

T733 Transformer

A similar inspection as performed on T732 was completed on T733. The one major exception is that the LTC compartment for T 733 was not inspected. There was no external evidence that warranted the inspection of the LTC compartment. As with the first transformer, the insulating material in the main tank was consumed by the fire. The following observations were recorded and these are supplemented with Photos 15 – 19 in Appendix A.1.

- The barrier board between the main tank and the LTC compartment was gone. However, most of the barrier between the selector and transfer switch compartments was still in place. The frame for the LTC barrier board was not deformed.
- Although the fire consumed much of the insulation in the LTC compartment, there was not the extent of mechanical damage as in unit T732.
- The HV and LV bushings had fallen into the tank. The connections from the windings were intact with both bushings.
- The conductors in the windings were bare as in T732; however, the conductors did seem to be deformed, as was the case in T732.

- The inside surfaces of the core were visible and no arc marks to the core were observed.
- No arc marks to the tank walls were visible.
- There was deformation of the steel for the tank walls. It appeared the deformation was probably due to the heat of the fire.
- The LTC compartment did not have the breach of the oil containment, as did T732.

Discussion of Observations

The two subject transformers were inspected and this was appropriate for comparison purposes. Unit T732 had more internal damage in the form of mechanical damage and conductor deformation than did T733. The LTC compartment in T732 was mechanically damaged internally and there was external damage that indicated an internal fault within the main tank or LTC compartment. The main tank and LTC compartment were both more damaged than with T733. The extent of the tank deformation for T733 was probably more from the heat of the fire than from an internal fault.

The coils were deformed in T732 whereas those in T733 did not appear to have been deformed. Thus, the observations from this limited inspection of the two units would indicate T732 failed internally and the oil was expelled through the LTC inspection door. This breach of the oil containment also allowed air to contact the oil and provide oxygen for combustion. From this scenario, it would appear the damage to T733 might have been collateral.

5.2 Inspection During Detailed Disassembly Of T732 And T733

The disassembly process began by removal of the top tank and LTC tanks from both of the transformers. Subsequently, the core was removed and the conductor could then be inspected. Both units burned dramatically as a result of the transformer failure and the paper insulation was totally consumed during the fire. The following observations were made during the detailed disassembly and the photo documentation is presented in Appendix A.2.

T732 Transformer

The remarkable aspect of this disassembly is that so much of the phase assembly was completely consumed in the fire that resulted from the failure. However, the conductors of the windings were still intact. The conductors were positioned differently from their original location due to the consumption of the paper insulation. This allowed the conductors to collapse into a “pile”. However, by measuring individual strands of copper one could identify the conductors in each winding. This is where the design information from ABB was extremely important. The objective was to examine the conductors for deformation, arc marks, broken strands, etc. The fire that occurred after the fault would not normally cause any of these effects on the conductors.

The shell form phase assembly is characterized as having numerous coils connected in series in each of the winding groups within the phase assembly. In this case, the number of coils in each winding group in Figure 1 is as follows:

TV Group, right end: 2 coils
Next LV Group: 4 coils
Next HV Group: 8 coils
LTC Group: 2 coils
LV Line Group: 8 coils
HV Line Group: 12 coils
LV Grd Group: 4 coils
TV Group, left end: 2 coils

Each of the coils is also shaped as a rectangular pancake coil. The rectangular coil has long straight portions along each side, known as the coil leg. In addition, the coil has a rectangular opening in the center of the coil to allow the core steel to be stacked in that region. This opening is known as the mold.

As the core was removed, it was inspected for any signs of flashover. No arc marks were found on the core material.

The observations made of T732 are documented in Photos 20 – 27 in Appendix A.2. The prominent observation of the phase assembly was two areas of broken conductor strands on the HV side of the phase. The region of the broken strands was in the outside leg of the coil, which is a region surrounded by core steel. One of the regions of broken conductors was in the HV line group. This was the one with the greatest amount of fractured conductors. The overall area was approximately 8 inches wide and 18 inches long. This is a large number of open conductors. The ends of the conductors were not characterized as shear surfaces but rather as conductors that had burned through by electrical arcing. There was also conductor deformation associated with the region of open conductors.

The second region of open conductors was located in the LV line group. These conductors were also burned through with the open ends showing the effects of having melted through. This region is smaller than that in the HV line group. The width of the affected region was approximately 6 inches wide and the length of the area was approximately 12 inches. As with the other location, the conductors were also deformed.

One of the significant observations of the conductor was that the copper was brittle. When bent, the conductor would suddenly snap without having to be bent back and forth several times. The conductor was originally soft annealed copper and this material would normally require several bending strokes to break the conductor. The unknown is whether the brittleness was the result of the fire or by overheating from prolonged high-current flow. Nonetheless, the copper was brittle and had a crystallized appearance. It is anticipated to have some metallurgical analysis on the copper.

The conductor was lifted from the bottom tank section and allowed an inspection of the entire surface of the conductor. The mold region was inspected and there was no deformation of conductor in this area. In addition, there were no open conductors in this area.

The coil pack was lifted revealing the lower end of the coils. The conductors in this area were intact. Thus, the only area with open conductors was along the leg on the HV side of the phase assembly.

The top tank section, bottom tank section, and LTC compartment were inspected in detail for any sign of flashover. There were no arc marks on any of the tank panels. There were several regions on the tank where the tank panels were bulged. Upon inspection, it was found that the major reason for the bulging was from air compartments becoming pressurized during the fire. The pressure increase was sufficient to permanently deform the tank panels.

Therefore, the significant finding in this unit is the two regions of open conductors in the leg region of the HV line group and LV line group.

T733 Transformer

This transformer was also disassembled since it also burned during the failure event and because it was also in the T1 bank. The main objective was to determine if there were differences in the condition of the phase assembly of this transformer and the T732 described above. The entire transformer had to be dismantled to the same point as T732 to make the determination. The disassembly of this transformer is documented with Photos 28 – 32 in Appendix A.2.

As the core material was removed it was inspected for evidence of flashover from the windings. No arc marks were found on the electrical steel.

The conductor was in a similar general condition as with T732 in that the consumption of the insulation allowed the conductor to collapse. There were no signs of conductor deformation or broken conductors in this transformer. The phase was removed from the bottom tank section, thus revealing all surfaces of the coil assembly. There were no indications anywhere of broken strands or deformation as was the case in T732.

The top and bottom tank sections were inspected and the result was the same as with T732. There were no flashover points on tank panels. The tank panels were also bulged in the same manner as with T732, due to the pressure build-up in air compartments. The LTC compartment was also inspected and there was a difference between it and the one in T732. The difference was that the barrier board frame in this unit was not deformed, as was the case for T732.

The inspection of T733 was unremarkable, i.e. the significance of this is that it may be concluded that the failure initiated in T732. The damage to T733 is collateral to that of T732.

T790 Transformer

This transformer was inspected since the phase assembly did not burn as a result of the failure of T732. The ensuing fire affected this transformer by damaging the UTH LTC. This transformer was inspected on 10/27/04 and the observations are presented photographically in Photos 28 – 32 in Appendix A.3. This transformer was one of three transformer in the T$ bank. It is identified with serial #7002116. All transformers in the T4 bank were manufactured as duplicates of the transformers in the T1 bank. Thus, all transformers in the T1 and T4 banks are the same design and are of similar age.

As expected, the phase assembly was intact with no indication of any thermal damage from the external fire. The internal surfaces of the tank panels are painted with a red primer and the primed surfaces were unaffected. The lead structure is situated above the top end of the windings and is the first structure encountered upon entering the transformer. The lead structure is fastened together with non-metallic bolts and nuts. The remarkable feature was that the hardware was tight. There was only one broken bolt found inside the transformer. This is remarkable for a transformer of this age. Not only was the structure tight, the leads were well supported and tightly held in place.

The LTC terminal board was not disturbed and the lead attachments were tight. The lead taping was also tight with no external indication of any overheating or mechanical damage. All LTC leads from the winding were in the proper location.

The winding and insulation structure was inspected in detail for any abnormal condition. In general, the phase was still tight along the axial axis. For a transformer of this age, one could have expected some degree of looseness. It was noticed that some of the formed pressboard insulation items were displaced vertically. This can occur during through fault events via oil pumping action. There was also some deformation of the vertical barriers between winding groups. These barriers are called washers and they are fabricated from sheets of pressboard. The deformation may be indicative of some movement of the coils. Although these deformations were evident, there was no specific evidence that would indicate this transformer has a fault in it. An important point to note is that one can only see about 10% of the phase assembly in a shell form transformer when the tank and core are still in place. Therefore, one can only state that the observations could indicate some coil movement may have occurred. This is an important observation since it could provide some insight into the condition of T732 prior to the transformer failure. It was appropriate to make this internal inspection.

6. Analysis of Data and Observations

The first area to review is the temperature rise of the copper during the long duration short circuit current. For this exercise the current during fault #5 will be analyzed since transformers T732 and T733 in the T1 bank carried this current. From the data presented in Section 3. the current magnitude was 9.15 PU for 19.746 seconds. The calculation of the winding temperature is based on all heat stored since the time for the current flow is much less than the time constant for the conductor in the windings. The winding time constant is usually in the order of 3 – 6 minutes. The time for the fault current was 19.746 seconds, thus the assumption to assume all heat stored is valid.

The temperature rise of the conductor with all heat stored can be expressed with the following relationship:

$\Theta_{cu} = (\text{watts/lb}_{cu}) / 3.04$

Θ_{cu} is temperature rise of conductor in °C/minute

The watts/lb for the LV winding is 5.9 and 5.4 for the HV winding at a load of 200 MVA. The fault current was calculated as 9.15 times the normal current at 200 MVA, thus the watts/lb during the fault is:

Watts/lb = $9.15^2 \times 5.9 = 493.96$, substituting into the expression above leads to:

$\Theta_{cu} = 493.96 / 3.04 = 162.49$ °C/min

The current flowed for 19.746 seconds, which is 19.746/60 = 0.329 min, thus the temperature rise in the conductor is:

$\Theta = 0.329 \times 162.49 = 53.47$ °C temperature increase over the operating temperature prior to the fault. If one assumes the temperature at the time of the fault was 35°C and the winding rise was 55°C, the total winding temperature would become:

$\Theta = 35 + 55 + 53.47 = 143.47$ °C

This temperature is the average winding temperature, not the hot spot temperature. The hot spot temperature would be ~20 – 30 °C higher. These temperatures are relatively short in duration. The point from this is that the conductor did not reach a temperature high enough to anneal it to significantly lower levels than its original value. Thus, the lengthy fault current most likely did not affect the strength of the copper but the length could have had an impact on the dynamic mechanical capability of the transformer. Thus, testing the conductor for strength and brittleness is not indicated from these calculations. Furthermore, the copper in both T732 and T733 was of similar brittleness and it may be concluded this is the result of the fire in both units.

During the investigation, the question was raised about the effects of the elevated winding temperatures that occurred in the short circuit event. The winding hot spot was predicted above to be in the range of 173°C. The results of R&D projects in the 1980s showed the effects of elevated winding hot spot temperatures. One of the manifestations was bubble evolution from the cellulose insulation in the vicinity of the hot spot. The bubble evolution was shown to occur at temperature greater than or equal to 140°C. The tests performed were simulations of overloading transformers for short or long term overloads. It has been shown subsequently that other variables have a major impact on the temperature of bubble evolution. First of all, the bubbles were determined to be water vapor evolved from the cellulose. Thus, the temperature for bubbles to be evolved is dependent on the water content of the paper at the time of the overload. The point here is that the critical temperature for bubble formation does not occur at a set temperature. The more important point relative to the present case is the time of application of the temperature. The R&D work involved loading the transformers for prolonged periods of time, as would be the case with overload conditions. The short circuit event for this transformer, although very long for a short circuit, is quite short when compared to an overload. The short circuit event was 19.7 seconds versus hours for a normal overload condition. The short circuit event is a transient event rather than a steady-state condition and the formation of bubbles from the paper takes time to develop. It would normally take minutes to even hours for bubbles to be formed during an overload condition and thus would be virtually nonexistent during the 19.7 second short circuit event. This is also one reason that the acceptable conductor temperature during short circuit events is 250°C.

During a short circuit event the current generates forces within the phase assembly that are proportional to the square of the current. The current is a sinusoidal function, which leads to the generated force being predominantly a $\sin^2$ function. The force is unidirectional in nature and results in an axial compression on the coils followed by relaxation and followed by another compressive force with a frequency of 120 Hz. This type of force becomes a pumping action on the coils. The oil in the cooling ducts along the surface of the coils is incompressible, which ultimately is forced vertically through the oil ducts with a high force. The prolonged duration of this fault would subject the insulation structure of this transformer to many more cycles of oil pumping than would be the case in normal fault duration of 2 seconds.

The internal inspection of T790 indicated some insulation items that were moved vertically out of position. It should be noted that T790 was not subjected to the long duration fault #5, thus the movement of insulation would have been exacerbated in T732 and T733 in comparison to that in T790. Unfortunately, the insulation was destroyed in T732 and T733 so this condition cannot be observed. However, there was indication of conductor deformation in the HV line group and the LV line group of T732. This movement would have been a reasonable result of the unidirectional force applied to the phase assembly for the prolonged period of time.

The conductors in T732 that were burned open are indicative of an internal arc in those two regions of the winding assembly. The amount of conductor having been involved in the faults in the T732 winding was indicative of a relatively large disturbance in the coils. From experience in disassembling other failed transformers, this type of disturbance can be due to turn-turn or coil-coil faults with power follow into the fault location.

The two fault locations were also located near the HV line terminal and the LV line terminals. This is significant since there is little transformer impedance in the circuit between either of these fault locations and the HV and LV power systems. The significance of this is that a high-energy discharge inside the transformer was necessary to cause a breach of the tank. It was observed that the LTC barrier board frame was deformed outward from the transformer side of the board. This indicates a high pressure developed on the transformer side. The breach in the tank occurred in the UTH LTC tank. An outward force from the transformer tank would have produced this effect.

Another aspect of the long duration fault was discussed earlier in this report. The magnitude of the current and the fault duration were compared with the Damage Curve In ANSI C57.109. According to this curve, the transformer was subjected to excess stress.

One may conclude from the various pieces of data that have been collected and analyzed that the 6/14/04 system disturbance had an influence on the failure of T732. The physical evidence and DFR data support the theory that T732 failed and subsequently caused the fire that engulfed the adjacent transformers in the T1 and T4 banks. The data suggests that the dynamic mechanical duty subjected on the transformer was more onerous than the thermal duty. The calculated temperature rise of the conductor was not high enough to cause additional annealing of the copper. There was possible deformation observed in T790 and it is reasonable that the units in T1 would have had more movement than T790 since T790 was not involved in fault #5.

There are important aspects of coil and insulation movement in transformers. First of all, the amount of movement is dependent on the amount of shrinkage of the paper insulation that has occurred through years of service. The transformer in T1 and T4 banks were manufactured with low-density calendered pressboard. This material has less long-term dimensional stability than does the high-density material that is routinely built into transformers by current manufacturers. Each transformer will have its own set of characteristics relative to shrinkage over time. One thing is certain, the insulation will tend to shrink with age and there is effectively no tightening process for shell form transformers.

In the situation at hand, the other transformers in the T4 bank may or may not be in similar condition as T790. The other transformers have not been inspected and to do so would only allow visual observation of a relatively small amount of the transformer active part. Thus, one may not be able to observe areas of deformation that are not visible from the top of the phase assembly. It may be possible to get an indication of movement by performing a frequency response analysis (FRA or SFRA) test on the transformers. The caveat in doing the test is that the original frequency response is not available. Some older transformers have been assessed by this test. It may be prudent for APS to discuss the potential of assessing these transformers with companies that perform these tests.

7. Most Probable Cause of the Failure

The failure of transformer T732 occurred in the relatively near proximity in time with the system disturbance that occurred on 6/14/04. The analysis of the data in Section 6. proposes the system fault resulted in damage to the phase assembly that was not sufficient to cause an immediate failure, but set forth the conditions that initiated an incipient condition that progressed into the ultimate failure of the transformer.

The deformation in the conductors of T732 indicates that movement had taken place. With no insulation remaining in the structure it is impossible to objectively state that a coil-coil or turn-turn fault developed in the transformer. It is known that if coil movement occurs there are various manifestations that may be evident from that movement as follows:

The coil-coil spacing may be reduced with the resultant reduction in dielectric strength between coils.
The movement can result in damage to the turn insulation, which can progress into a turn-turn fault.
The movement of insulation items out of place from oil pumping can lead to a coil-coil fault due to insufficient insulation between coils.

Regardless of the processes listed above, the fact is there were coil faults in the winding of the transformer subjected to a heavy fault duty. One or more of the previous itemized processes may have been involved, however, the root cause is not these processes, but rather the process that initiated the process (es) in the first place. Thus, the most probable cause of the transformer failure is damage that resulted from the 6/14/04 system fault. It should be noted that a fault in excess of 19 seconds is very long compared with the capability normally designed into transformers. On the one hand, it is rather remarkable the transformer survived the lengthy fault event without failing at that time.

8. Recommendations

The analysis of the data surrounding this failure event did not indicate any deficient operational processes on the part of APS personnel. The maintenance practices appeared to be adequate and the historical data did not exhibit any incipient failure mode.

The only abnormal data involved the system fault on 6/14/04. The abnormality involved the duration of the fault associated with the T1 bank. There were multiple faults to which the T1 bank was subjected and it was fault #5 that resulted in the heaviest duty for the T1 bank. The duration of the fault was much longer than normally anticipated in transformer design. The duration was also much longer than the two-second value established in ANSI Standards.

The recommendation from this analysis is that APS should establish system protection schemes that will limit the duration of system faults to two seconds, or to limit the current magnitude and duration to values below the damage curve published in ANSI Standards.

9. Conclusions

The failure event at the Westwing Substation was an extraordinary event. There was so much collateral damage to other transformers in the T1 bank and the adjacent transformer bank. This is more damage than is ordinarily observed when one transformer fails.

The data analyzed supports the conclusion that transformer T732 failed and was the only transformer in the T1 bank to fail. The internal failure caused high pressure within the transformer tank. A breach of the oil seal occurred when the internal pressure caused a failure of the oil seal of one of the inspection doors on the Model UTH LTC. The barrier between the transformer oil volume and the oil in the LTC was broken during the failure, which resulted in draining oil from the main transformer tank to the outside environment. The ensuing fire consumed the adjacent units.

The inspection of transformers T790 and T733 indicate they were the victims of the burning oil from T732. The inspection of T790 also indicated movement of the windings may have been the precursor of the final failure event. The 6/14/04 system fault duration was so long that winding movement most likely occurred in T732 since there was evidence that movement had occurred in T790, although it had not progressed to the point of failure.

There was definite evidence of winding failures in T732. There were large areas of conductor fractures, deformation, and melted material. The conductor movement was most likely sufficient to result in coil-coil and/or winding-winding faults. The HV line portion of the series winding was definitely involved, which is the highest voltage portion of the phase assembly.

The data support the scenario by which the transformer failed as a result of damage incurred during the previous system fault.

10. Appendix A
Photographic Documentation

Appendix A.1
Inspection Prior to Disassembly

Photo 1

This photo shows one of the corners of the lowe tank section of the phase 2 transformer of the T1 bank. The dark area was an area of failure of the base metal of the intersecting parts of the tank structure. This is indicative of high stresses in this region of the tank.

Photo 2

In this view the LTC compartment of the phase unit of the T1 bank is shown as viewed from segment 2 of the tank. This breach to the oil system occurred during the failure event. This was the only unit that had this type of damage. It is also indicative of fault pressures having occurred in the LTC compartment.

Photo 3

In this view of the phase 2 unit one can see the inspection door blown open on the left side of the LTC compartment as well as a deformed inspection door on the front off the LTC compartment. In this view it is the inspection door that is in the center of the photo. Although the bolts have not failed and the oil seal was not broken, it is obvious that high pressures were developed in the outer compartment of the LTC.

Photo 4

This photo was taken inside the phase 2 unit. The structure to the right is a portion of the core steel and the windings are to the left. The open area was originally filled with insulation that was consumed during the fire. The long tube is the conductor for the LV bushing.

Photo 5

This is another view of the top of the phase. The conductors are shown collapsed, which took place as the insulation burned away. When the insulation was consumed there was no structure to support the radial build of the pancake coils. As such, the coils could only be distinguished if one knew the conductor sizes in each winding. This information was not available at the time of this inspection/

Photo 6

This is a view of the phase on the LV side of the transformer. A portion of the LTC tap leads is shown to the left.

Photo 7

This is a view of more of the LTC leads from the phase to the LTC compartment. There were no indications of any conductor damage of the tap leads.

Photo 8

This is a view of the internal end of the HV bushing. As can be seen, the fire destroyed most of the internal portion of the condenser.

Photo 9

This view is of the LV leg of the phase from the top. From this vantage point, it did not appear as though any major deformation occurred in the conductors in this region.

Photo 10

This view shows the routing of the LTC tap leads toward the LTC compartment. The opening in the tank wall is not normal. There is an epoxy barrier board with connectors molded into the board so as to provide a separation between the transformer oil volume from the oil volume in the LTC compartment. The barrier board was destroyed in the failure. The frame for the board was deflected outward from the transformer side, thus the board may have blown out during the failure rather than having been burned in the fire.

Photo 11

In the background of this photo is another opening depicted by a rectangular frame. There is normally another barrier board mounted in this frame to form a barrier between the transfer switch compartment and the selector switch compartment. The barrier board was destroyed in this unit as well.

Photo 12

This is a view of the phase along the leg on the HV side of the transformer. Near the middle of the photo there is deformation of the conductor. It appeared the deformation was located along the leg of the coil further down the height of the coil that was not visible from the top of the phase.

Photo 13

This is another view of the HV side of the phase. The deformation is more prominent in this view.

Photo 14

This a view of the inside surface of the top of the transformer tank. This view shows deformed braces on the tank. These may have been deformed during the failure due to internal pressure or by the heat of the fire.

The following photos in this appendix are associated with the phase 3 transformer in the T1 bank.

Photo 15

This is a view of the leads routed into the LTC compartment. As with the phase 2 unit, the barrier board between the transformer and the LTC compartment is destroyed. A major difference is that the board between the transfer switch compartment and the selector switch compartment is still in place. Although not shown, the inspection doors in the LTC compartment were not deformed and the oil seals were not broken.

Photo 16

This is a view along the LV side of the phase. There were no obvious areas of deformed conductor along this side of the windings.

Photo 17

As with the phase 2 transformer, the bushing in this transformer was also destroyed. This is the internal end of the LV bushing.

Photo 18

This is a view of the phase along the HV side of the windings. There was a distinct difference between the two transformers with this one not showing the indications of deformed conductors.

Photo 19

This is a view of the barrier board between the transfer switch and selector switch compartment. Although the surface was burned, the board was essentially intact.

Appendix A.2
Inspection During Disassembly

The following photos are for the phase 2 transformer

Photo 20

This is a view of the active part being disassembled with the top tank removed. A portion of the core has already been removed at this point. Note the position of the conductor as it is wrapped around the core steel through the center of the coils. The design information was available at this point and conductors were measured to determine the winding to which they were associated.

Photo 21

This is a view from the LV side of the phase. The majority of the jumbled conductor in this view is from the LTC leads that have no support. All of the core has been removed at this point.

Photo 22

This is a view of the windings from the HV side. There are two areas of major conductor damage on this side of the phase. There is one area toward the right end of the phase where the conductors are broken and melted. The other area is toward the center of the phase.

Photo 23

This is a view of the area toward the center of the phase. The conductors are broken and melted.

Photo 24

This is an overall view of the HV side of the phase. The areas of fault in the conductors are in the center and the right end of the phase.

Photo 25

This is a close-up view of some of the damaged conductors on the HV side. The conductors are twisted, broken, and melted.

Photo 26

This close-up view shows a large number of melted conductors on the HV side of the phase.

Photo 27

In this view one can see a large piece of solidified molten copper. A relatively large amount of energy was dissipated in this region to melt such a large portion of the winding. This area involved multiple coils, but it was not possible to determine the exact coils due to the collapse of the coils after the fire consumed the insulation.

The following photos in this appendix are associated with the disassembly of the phase 3 transformer.

Photo 28

This is a view of the phase 3 transformer before the core has been removed.

Photo 29

This is a view from the HV side of the phase. There is an obvious difference between this unit and the phase 2 transformer. The conductors are not deformed or burned in this transformer.

Photo 30

This is a view from the LV side. As with the HV side the conductors are not deformed. The conductors that appear deformed were cut and pulled into this position in the disassembly process.

Photo 31

This is a view into the center hole through the phase assembly. The conductors are straight and are not deformed in this region.

Photo 32

This is a view of the phase being lifted from the lower tank section.

Appendix A.3
Internal Inspection of Transformer T790

Photo 33

This is a view of the insulation at the top of the phase assembly for the HV line portion of the series winding. Note the vertical displacement of the formed angle in the left of center part of the photo.

Photo 34

This is a view down onto the top of the phase assembly. The thin pieces of material are pressboard sheets referred to as washers. They go the full height and full width of the phase assembly. Note the bulge in the washers, which indicate some movement along the horizontal axis of the phase.

Photo 35

This is another area showing deflected washers. This is a different region from the previous photo.

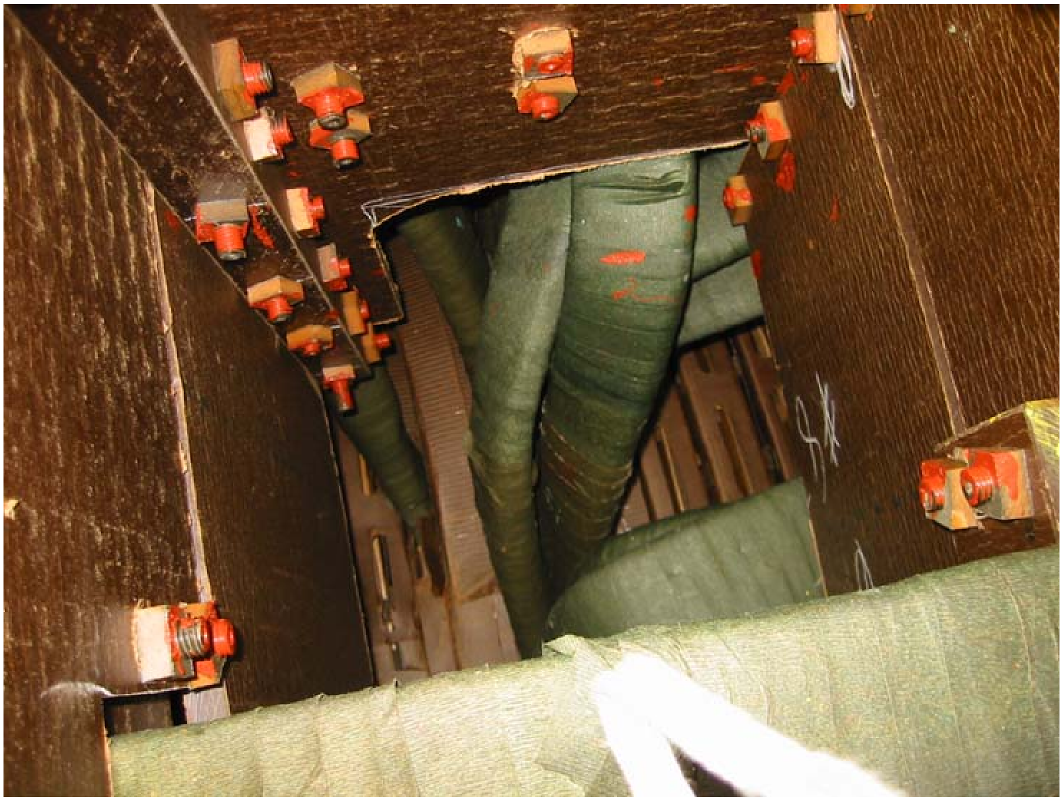
Photo 36

This is another area of deflected washers along the horizontal axis of the phase.

Photo 37

This photo shows the terminal board that was destroyed in transformers for phases 2 and 3 of the T1 bank. The leads are in their correct placement.

Photo 38



This is a view of the DETC taps. The leads are routed vertically upward from the phase to the DETC mounted above the phase.