# MATHEMATICAL MODELLING OF BUBBLE EVOLUTION IN TRANSFORMERS

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Abstract - A mathematical model of a small subsystem within a transformer winding has been constructed to define operating conditions under which free bubbles are likely to be evolved. The model is based on the characteristics of the component materials in. the subsystem. Its predictions have been correlated with the observed performance of physical models to establish confidence in its validity and it has been exercised to demonstrate the role which rnany transformer operational and constructional variables play in establishing conditions suitable for bubble formation.

## INTRODUCTION

Concern has developed in recent years about the possibility of bubble formation in power transformers under certain conditions of operation. Free gas within the oil/cellulose insulation system of a transformer is a cause for concern because of the extremely low dielectric strength of the gas relative to oil or cellulose. In fact, evolution of free gas during service operation of power transformers has been known to produce dielectric breakdowns in several instances [1,2,3.] Three mechanisms are recognized by which gas bubbles can be generated.

1. Super saturation of the oil with a blanket gas.
2. Thermal decomposition of cellulose insulation.
3. Vaporization of adsorbed moisture in the cellulose.

The gas bubbles evolved in the first case would be principally the blanket gas (usually nitrogen). In the other two cases the bubbles would also contain a large fraction of blanket gas (if one were present), as well as smaller amounts of any other gases dissolved in the oil. Additionally, the bubbles formed from thermal decomposition of cellulose would contain a combination of carbon monoxide, carbon dioxide, and water vapor. There would be additional water vapor in the bubbles in the last case.

The first mechanism occurs generally throughout the insulation system after a transformer with a gas blanket oil preservation system has been operating heavily loaded and the load is suddenly removed, allowing the transformer to coo! quickly. The fact that the hot oil has been thermally expanded reduces the volume of the gas space, producing a relatively high gas pressure and high dissolved gas
Content within the oil.

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When the oil cools quickly and its volume is reduced, the volume of the gas space is suddenly increased and the gas pressure 1s reduced. At the lower temperature and pressure, the oil contains more gas than 1t can hold. In the supersaturated condition, free gas is spontaneously released throughout the oil volume. In addition to
free gas bubbles in the bulk oil, it has been reported[4] that some of the gas bubbles are evolved and entrapped within the wraps of conductor insulation, thus reducing the dielectric strength of the windings.

The second and third mechanisms take place at a heated conductor surface, and they involve an interaction between the conductor and it's over wraps of cellulosic insulation. The existence of the these two mechanisms has been demonstrated by several investigators [4, 5, 6, 7, 8] although it is generally difficult to conclusively separate the two in a physical experiment. However, Rouse[8] did collect gas bubbles evolved from cellulose heated to relatively low temperatures ( 125 -150°C) and pass them through a mass spectrometer to identify them as exclusively H20. Cellulose degradation apparently did not contribute directly to bubble formation at these temperatures. In any event, the effect of the thermally evolved free gas at the conductor surface, under the insulation wraps, has been demonstrated to be significant reduction of the dielectric strength of the insulation system [6, 7]

Recognition of the possibility of gas bubble evolution within an operating transformer is not sufficient to totally avoid its occurrence. A basis is needed for prediction of the specific circumstances which can lead to the generation of bubbles, or, conversely, identification of circumstances which assuredly will avoid the generation of bubbles. This paper presents a concept for a simple model which can provide useful insights into the occurrence or avoidance of bubble formation i n transformer insulation systems.

## FUNDAMENTAL MECHANISM OF BUBBLE FORMATION

In order for a gas bubble to form and grow within a volume of liquid, the bubble must press away the surrounding liquid. The gas within the bubble must develop an internal pressure sufficient to overcome the forces constraining it, namely, the interfacial tension force of the liquid, the gravitational force acting on the column of liquid above the bubble, and the force of the atmospheric pressure acting on the surface of the liquid.

For practical considerations, the first of these forces can be neglected, since the interfacial tension force is extremely small {˜ 1-100 dyne cm or ˜ 0.2 mm Hg) for transformer oil and gases of interest. The hydrostatic pressure force for oil is also small (1.7 mm Hg/inch of oil), and will be of minor consequence unless the site of the bubble formation is deep within the liquid. In general, the principal constraining force of concern is the static pressure on the liquid surface. For power transformers, the static pressure over the liquid is usually 760 mm Hg or greater
.

A gas dissolved in a liquid has an "escaping tendency"; that is, a drive to maintain equilibrium with its gas phase. At equilibrium, the concentration of a dissolved gas is proportional to the partial pressure, P, of that same gas over the liquid. The drive of the dissolved gas to escape is exactly balanced by the drive of the gas over the liquid to enter the liquid, so the concentration of the dissolved gas is at steady-state. Henry's Law states that the concentration, $C^i$, of a single gas, i, dissolved in a liquid is proportional to the partial pressure of that gas, $p^i$ over the liquid:

$$C^i = K^i \text{ x } P^i \qquad (1)$$

where the concentration is given in parts per million (ppm) by volume, the pressure is in atmospheres, and $K°$ is a proportionality constant which is dependent on temperature.

$$K^i \approx \exp (A^i / T) \qquad (2)$$

T is absolute temperature in degrees Kelvin (°K). $A^i$ is a constant which is different for each gas-liquid combination and can be algebraically either positive or negative. ($K^i$ and its dependence on temperature is a reflection of the intermolecular interactions peculiar to each gas-liquid combination.)

If, at constant temperature, the partial pressure of the gas over a liquid is increased, additional gas will dissolve into the liquid to reach a new equilibrium concentration as defined by Henry's Law. Like-wise, if the temperature changes so that Ki - becomes larger while the pressure of the gas over the liquid is held constant , additional gas will again dissolve. The reverse of each of these processes can occur, causing gas to come out of solution. In a situation where the reduction in pressure of the gas over the liquid is sufficiently slow for the dissolved gas to diffuse to and across the gas-liquid interface, the gas will "steam" away. The "escaping tendency" tracks the slow decrease in the external partial pressure. However, if the pressure of the gas over the liquid drops so rapidly that the dissolved gas does not have time to diffuse to the surface, the gas concentration in the liquid will exceed that prescribed by Henry's Law and an unstable condition results. The "escaping tendency" defined by Henry's Law will be greater momentarily than the pressure over the liquid and internal bubbles will form within the liquid to reli- eve the excess concentration.

Warm beer bubbles and foams when the bottle cap is removed and the pressure of carbon dioxide (C02) in the neck of the bottle is suddenly released. Colder beer bubbles and foams less, in part because the pressure to be released in the neck of the bottle is less, but also because CO2 is more soluble in cold water; that is, $K^{C 0 2}$ increases with decreasing temperature ($A^{CO2}$ is algebraically negative).

The formation of gas bubbles in the oil of a transformer with a nitrogen blanket oil preservation system when the oil temperature is reduced rapidly is another example of this phenomenon. Here the principal role of the temperature change is to cause reduction of the oil volume, thus allowing expansion of the gas over the oil and a reduced gas pressure.

This tends to produce" an unbalanced "escaping tendency" for the dissolved nitrogen within the oil, which was in equilibrium with blanket gas at a higher pressure. A secondary effect of the temperature reduction is to produce a lowering of the Henry's Law constant for nitrogen, which permits a higher concentration of dissolved gas for a given gas pressure over the oil. To a degree this offsets some of the unbalanced "escaping tendency", but it is not sufficient to prevent the formation of free gas bubbles within the oil.

A bubble forms in a liquid, then, as a result of a pressure unbalance when the system attempts to follow an abrupt excursion toward a new equilibrium condition. In this circumstance the summation of the internal partial pressures of the gases disso!ved within the liquid exceeds the static pressure over the surface of the liquid.

The excursion can be due to a change in temperature or pressure of the entire system, or it can be due to a local change, particularly a change in temperature. As an example, if a lighted match is thrust into quiescent beer, bubbles will form on the extinguished match head. The match is hot enough momentarily to decrease $K^{C02}$ locally so that the quotient exceeds $P^{stat}$.
In general, transformer oils containing gases behave as ideal dilute solutions in that the solubility of one gas is independent of the presence of any other gas. This is to say that $K^{N2}$ is the same whether C02 is present or not and $C^{N}2$ does not depend on $P^{CO2}$. However, gases behave collectively, in| forming bubbles. When their combined "escaping tendencies" exceed the total static pressure af bubble will form. With two gases, "a" and "b", present, the sum of the "escaping tendencies" is

$$(C^a/K^a) + (C^b/K^b) = p^a + p^b \qquad (4)$$

If both $K^a$ and $K^b$ decrease with increasing temperature, the sum $P^a + P^b$ may exceed the external static pressure on heating the system and a bubble containing both gases may form. Even if $K^b$ increases modestly with temperature, a bubble can form if the quotient $C^a/K^a$ increases more rapidly than the quotient $C^b/K^b$ decreases as the temperature is raised. On the other hand, if $K^b$ increases much more rapidly than $K^a$ decreases with increasing temperature, the situation could be reversed and bubbles would occur on cooling the system, rather than on heating it.

The examples discussed thus far have centered around formation of bubbles as the concentrations of dissolved gases attempt to arrive at a new equilibrium condition following changes in temperature or external pressure. Local concentrations can also change as a result of chemical or physical reactions within the system. Thermal decomposition of cellulose in an operating power transformer is an example of a chemical reaction which can increase the local concentration of gases in the oil.

The primary pro-ducts of thermal decomposition of cellulose are water, C02, and CO. Heating the oil/paper insulation at a sufficiently high temperature will generate gases more rapidly than they can diffuse away into the surrounding oil. The local concentration of gases will build to the point where the summation of "escaping tendencies" exceeds the static pressure and a bubble forms. On cooling, the rate of gas generation slows, and any entrapped bubble will slowly shrink as the gases dissolve into the oil and diffuse away.

Desorption of water from the cellulose in the oil/paper insulation system is an example of a physical reaction which can increase the local concentration of gases in the oil to produce bubbling. Water distributes itself between the oil and paper in such a fashion that the concentrations of water in the two media are in equilibrium with the water vapor pressure over the insulation system. The equilibrium of this distribution is affected by temperature, with the oil holding a greater concentration of water at higher temperatures than at lower ones. However, over the range of possible transformer operating temperatures, a very high percentage of the total mass of water in the system is contained in the paper. (In a subsystem containing equal volumes of pap$^{er}$ with 0.5% moisture content by weight and transformer oil, the paper will contain approximately 99.9% of the total weight of water when the subsystem is equi-librated at 80°C. In effect, the paper in a trans-former acts as an almost infinite reservoir to supply additional water to the oil as temperature increases and to adsorb excess water as temperature decreases.

Thus if a rapid increase in temperature occurs in a paper-insulated conductor, the concentration of water in the oil impregnating the paper will suddenly Increase, as will the "escaping tendency" of water vapor. This partial pressure of water vapor will then be added to partial pressures exerted by the other gases already present in the oil, and the opportunity exists for the summation of local pressures to exceed the static pressure over the oil. Such a condition can result in the evolution of free gas bubbles.

Bubble formation then reflects a complex inter-play of variables. It results from an abrupt departure from equilibrium through some change in pressure, local temperature, and/or local concentration of gas. The last of these three elements depends on the mass transport available to redistribute local concentrations of gas , hence it depends on the surroundings and the degree of mixing. All of the gases present operate together to control the initiation of bubbling. In the next section an attempt is made to quantify the effects of the variables which influence the formation of free gas bubbles, using a simple model of a portion of an operating power transformer.

## A GÁS BUBBLE EVOLUTION MODEL FOR POWER TRANSFORMERS

The region within a transformer which is most vulnerable to bubble evolution is a high voltage .conductor, either in the winding or leads, with its over wraps of paper insulation. This region is vulnerable because it operates at dielectric stresses .which can produce partial discharges in gaseous media.. Consider a model of one small subsystem of this type within the windings, as shown in the sketch of Figure 1.

The subsystem is made up of a conductor, the several wraps of paper which surround it, and the oil which impregnates the paper and fills any minor voids between the paper wraps or between the paper and the conductor. (This oil will be referred to as "local oil°.) Analytical attention will be focused on the Innermost wrap of insulation adjacent to the conductor and the local oil. In order to examine the performance of this subsystem for a variety of possible transformer operating conditions, the following simplifying assumptions have been made.

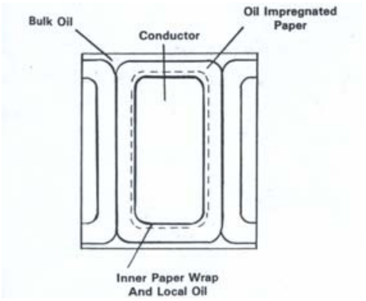


Figure 1: Insulated Winding Conductor Subsystem Within A Power Transformer.

1. The paper insulation wrap will serve as an infinite water reservoir for the local oil. (See discussion in the previous section.)

2. During the period of a thermal transient (up to one hour) the outer paper wraps will serve as a barrier to prevent alteration of local concentrations of gases or water vapor by diffusion inward from or outward to the bulk oil.

3. The inner wrap of insulation and the local oil will assume the same temperature as the conductor surface.

4. Henry's Law constants (ppm by volume-$cm^3$ NTP of gas x IQo/$cm^3$ oil at 25°C/atm) for non-condensible gases determined at temperatures of 80°C and below[9] can be extrapolated to higher temperatures as shown in Figure 2. A specific gravity of 0.885 (150C/15°C} and a coefficient of expansion of $0.68 \times 10^{-3}$ $cm^3/cm^3/°C$ were assumed for the oil.

5. The Henry's Law constants for water in Figure 2 are correctly derived from the saturation concentration of water in oil equilibrated with liquid water[9], together with the vapor pressure of water at the equilibration temperature (eg.-for T = 25°C, $C^{H2O}$ = 60µg/g, Pv=23,5mmHg,
K = 1940 ppm by vol/atm) and the assumption that water vapor behaves as an ideal gas.

6. Water vapor pressure equilibrium data for the paper insulation will conform to the character-shown in Piper 's[10] chart for Kraft
Paper (See Figure 3.)

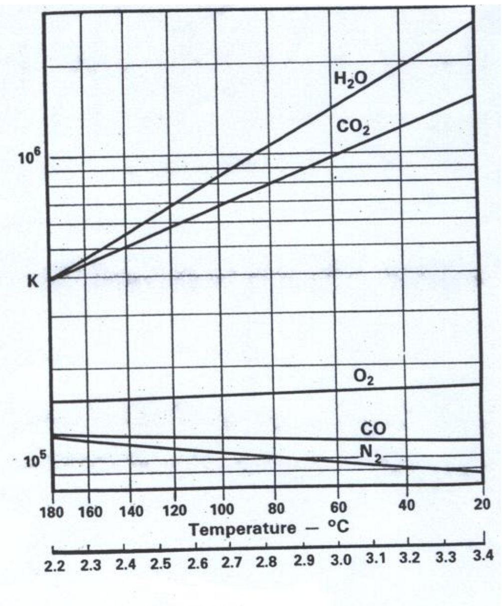


Figure 2:Henry's Law Constants (ppm vol/atm) For Common Gases In Oil With Specific Gravity of 0.885 (15°C/15°C) and a Coefficient of Expansion of 0.68 x $10^{-3}$cm$^3$/cm$^3$/°C.

The general procedure for applying the model involves definition of a stabilized operating condition at which the system has reached a state of equilibrium (transformer load, conductor temperature, insulation moisture level, and pressure of a blanket gas over the oil or dissolved gas content within the oil). Then an abrupt change in load or one of the other initial conditions is introduced. Thermal behavior of the winding conductor or oil is calcula-ted using equations from the industry loading guides, ANSI/IEEE C57.92-1981 (or transformer design equations may be used, if desired).

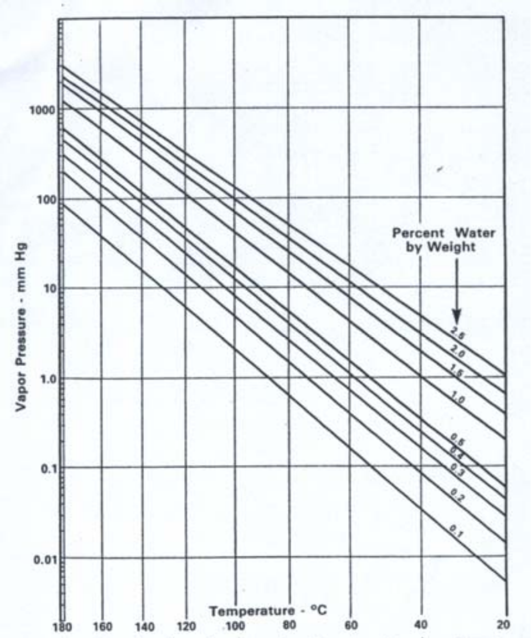


Figure 3: Equilibrium Chart Relating Water Vapor Pressure Over Oil To Water Concentration In Kraft Paper Versus Temperature (Redrawn From Piper[10]). Note: Piper's published chart does not extend above 110°C, but it is based in part on data from Houtz and McLean[11] which went up to 150°C. Piper's curves have been extrapolated to 180°C for use in this paper.

Partial pressures (or "escaping tendencies") of gases or vapor within the local oil in the model subsystem are determined from equation (1) and Figures 2 and 3 for the conditions which exist at any specific time after the change from initial conditions. The summation of partial pressures is then compared to the static pressure over the oil, according to equation (3), to see if there is a pressure unbalance which could cause internal bubble formation. (Thermal decomposition gases can also contribute to the partial pressure in the local oil, but this subject will be treated in one of the example cases in the next section.)

## APPLICATION OF THE MODEL

The model now can be exercised for some typical transformer operating conditions.

### Case 1. Sudden Drop of Load - Nitrogen Blanket

Assume that a transformer having a load loss to no-load loss ratio equal to 4 is operating at full load with the following steady-state temperature conditions:
Ambient Temperature = 25°C
Top Oil Rise Over Ambient = 45°C
Hottest Spot Conductor Rise Over Top Oil = 30°C
Hottest Spot Conductor Temperature = 100°C

Assume further that the volume of the gas space over the oil at 25°C is 8% of the total oil volume at that temperature. At steady-state full load, the pressure in the gas blanket will be approximately 1140 mm Hg (for a 7.5 psig automatic gas seal oil preservation system). Moisture content of the conductor insulation is assumed to be 0,.5% by weight. Under these conditions, the water vapor pressure in the local oil will be 15 mm Hg (from Fig. 3), so the partial pressure due to nitrogen in the oil must be 1125 mm Hg to balance the total gas blanket pressure of 1140 mm Hg. This partial pressure corresponds to a nitrogen concentration in the oil of 155,500 ppm by volume (NTP) using equation (1) and a value of $K^{N}2$ = 105,000 at 100°C from Figure 2.

At this point, assume that load is dropped. The hottest spot conductor rise over top oil will fall quickly, because the winding time constant is always small (assume 10 minutes in this case). At no load, the new steady-state hottest spot conductor rise over top oil is zero and this value will be reached in a time period of about three time constants, or thirty minutes.

Top oil rise over ambient temperature will also be falling, because, at no load, the Tosses will be only 20% of the full load losses (from the loss ratio of 4). However, the oil time constant is on the order of hours (two hours will be assumed for this case) and the oil rise will fall more slowly. The new steady-state oil rise over ambient is 9°C and the oil rise will have fallen from 45°C to 37°C after thirty minutes (based on loading guide equation calculations). Thus thirty minutes after load is dropped, temperature conditions will be:

Ambient Temperature =25°C
Top Oil Rise Over Ambient = 37°C
Hottest Spot Conductor Rise Over Top Oil = 0°C
Hottest Spot Conductor Temperature = 62°C

The 8°C reduction in oil temperature will result in only a 0.6% reduction in oil volume, but this corresponds to a 7% increase in the gas space.

Thus the blanket gas pressure over the oil (nitrogen plus water vapor) will drop from 1140 mm Hg to 1060 mm Hg. For the new temperature of the conductor (and inner wrap of paper), the water vapor pressure in the local oil will be 1.4 mm Hg (from Fig. 3). The concentration of dissolved nitrogen in the local oil is assumed unchanged and equation (1) can be utilized again to calculate a new partial pressure exerted by the nitrogen in the local oil. Using a value of $K^{N2}$ = 97,100 at 62°C:

$P^{N}2$=(155,500/97,100)x760= 1217 mm Hg (5)

The summation of the partial pressures exerted by gases in the local oil now exceeds the static pressure over the oil.

$P^{H2O} + P^{N2}$ = 1.4 + 1217 = 1218.4 mm Hg
> pstat = 1060 mm Hg (6)

This 15% excess pressure represents supersaturation of the oil with gas and water vapor, a condition suitable for bubble formation. 11 is evident that the unbalance comes about almost exclusively because of the reduced static pressure over the oil.

<u>Case 2</u>. <u>Sudden Increase of Load - Nitrogen Blanket</u>

Assume that the transformer of Case I is again operating at full load steady-state conditions.

Further, assume now that an overload is applied for a hort time, so that the conductor temperature rise over top oil increases, but the bulk oil temperature remains essentially constant. (If the oil tempera-t»re did increase slightly, the oil would expand, but the automatic gas seal system would bleed a small amount of gas to maintain the blanket gas pressure at ?140 mm Hg.)

The summation of partial pressures of nitrogen and water vapor has been calculated for several possible conductor hottest spot temperatures, but one sample calculation will suffice to demonstrate the method.

At a conductor temperature of 150°C, the partial pressure of water vapor exerted i n the local oil by O 5% moisture of the content paper is 180 mm Hg (Fig. 3). The partial pressure of nitrogen can be calculated from its initial concentration, 155,500 ppm , using a new value of $K^{N}2$ = 114,100 from Fig. 2.

$p^{N2}$ =(155,500/114,100) x 760 = 1036 mm Hg ( 7 )

Thus the summation of partial pressures exerted in the local oil near the conductor Is 1216 mm Hg, which represents a 6.7% unbalance over the blanket gas pressure and again indicates a condition suitable for bubble formation.

This calculation has been repeated for intermediate temperatures between 100°C and 150°C and the results are plotted in Figure 4. 11 can be seen that the partial pressure due to nitrogen decreases in an almost linear fashion as temperature Increases, but the partial pressure exerted by water vapor Increases In an accelerating fashion.

The result is that the summation of partial pressures falls at first and then rises rapidly, so that the "escaping tendency" begins to exceed the blanket gas pressure above 133°C. This suggests that at temperatures In the vicinity of 140°C conditions become favorable for the formation of bubbles when the local moisture content of the paper at the conductor is 0.5%.

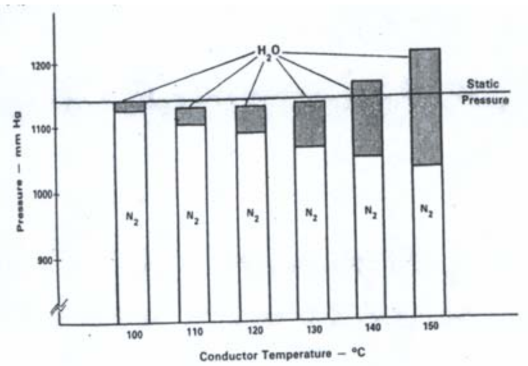


Figure 4: The Summation Of Partial Pressures Of Nitrogen And Water Vapor Exerted In Local Oil As The Conductor Temperature Is Raised Above An Initial 100°C Equilibrium Condition. Nitrogen Blanket Oil Preservation System And 0.5% Moisture in The Conductor Insulation.

### Case 3. Effect of Moisture Content of Paper

The calculations of Case 2 nave been repeated for a variety of moisture contents in the paper to demonstrate the role of that variable in establishing conditions favorable for bubble formation. Curve "A" °f Figure 5 shows the fashion in which the water content of the cellulose influences the critical conductor temperature for which the summation of partial pressures of gases in solution just exceeds the pressure of the blanket gas.

This figure is based on an initial conductor temperature of 80°C, rather than the 100°C of Case 2, because it will be used in a later section for comparison with experimental results. These model calculations predict that relatively wet conductor insulation will be much more vulnerable to low temperature bubble evolution than dry insulation. For reference, 1t is generally believed that a new transformer will have less than 0.5% by weight moisture in the insulation.

### Case 4. Effect of Blanket Gas Pressure

Automatic gas seal oil preservation systems are available which limit the maximum blanket gas pressure to values lower than the 7.5 psig assumed in Cases I- 3. One earlier gas-oil seal system main-tained essentially one atmosphere of blanket gas pressure for all operating conditions. The effect of blanket gas pressure can be seen by comparing curves "A" (1.5 atm.) and "B" (1.0 atm.) In Figure 5. The higher blanket gas pressure suppresses bubble evolution by 10-15°C for a given moisture level.

### Case 5. Effect Of Elimination Of Blanket Gas

Modern constant pressure oil preservation systems employ an oil expansion tank in which the oil is separated from the external atmosphere by a bag or membrane. Since the transformer oil is deaerated in the initial vacuum filling operation, the dissolved gas content with such an oil preservation system is generally much lower than with a gas blanket system. Some air will permeate the membrane over a period of time, but typical nitrogen contents in the membrane-type constant pressure systems range from 10,000-50,000 ppm.

In contrast, the nitrogen concentration for the Case I (1.5 atm.-0.5% H20) automatic gas seal example corresponds to about 145,000 ppm and the concentration for the Case 4 (1.0 atm.-0.5% H20) example corresponds to about 95,000 ppm. At the critical temperature of 133°C for 0.5% H2O on the "B" curve of Case 4, the summation of the "escaping tendencies" in the local oil near the conductor would be reduced to 431 mm Hg with a membrane-type constant pressure system (assuming 50,000 ppm of nitrogen in the oil), which is far below the static pressure of 760 mm Hg.

Viewed from another perspective, the critical temperature for the possibility of bubble formation would be raised from 133°C to 176°C.

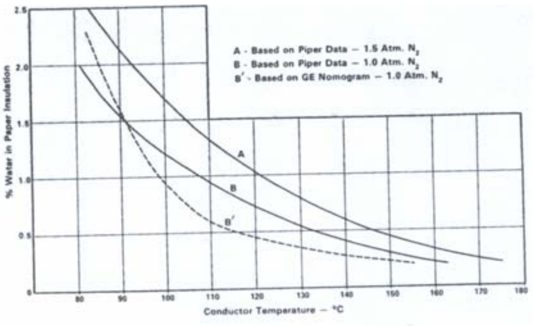


Figure 5: Critical Temperature Above Which Conditions Are Favorable For Bubble Formation. (Summation of partial pressures of gases in solution in the local oil at the conductor just exceeds the. pressure of the blanket gas over the bulk oil.)

### Case 6. Effect Of Initial Stabilized Load

The initial effect of starting from a low stabilized loading condition (low insulation and oil tempera-tures) is that the oil contains a lower concentration of nitrogen. This results in a lower partial pressure exerted by nitrogen when the local oil hear the conductor is heated during heavy loading, and a lesser tendency for bubble formation. However, there are other factors to be considered. To this point, moisture content of the insulation has been treated as an independent variable. The moisture content of the Insulation at the surface of the hottest spot conductor is, in fact, a dependent variable. It will depend not only on the total amount of moisture sealed within the transformer, but also on the relative temperature of the rest of the cellulose in the insulation system.

With no load on the transformer and uniform temperature throughout the system for a long period of time, the moisture will distribute uniformly in all parts. After the transformer carries load for some time, the hotter insulation will have become dryer and the moisture which it sheds will move into cooler insulation.

Consider a simplified example in which three e different temperature areas are identified within the Insulation system:

A. Conductor insulation at or close to hottest spot temperature.

B. Conductor insulation at average winding temperature.

C. Major insulation, lead supports, etc. at average oil temperature.

In a medium size power transformer, the weights of Insulation in each category are approximately:

A = 500 pounds

B = 6000 pounds

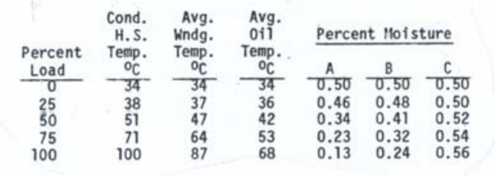
C = 27000 pounds.

With an initial moisture content of 0.5Í by weight in the insulation, the total system contains 167.5 pounds of water (assuming negligible e weight of water in the initial oil fill).

At each stabilized load condition, the "A", "B", and "C" insulations at their respective temperatures and the oil must all be in equililbrium with the water vapor pressure over the system. To calculate the appropriate moisture content for each insulation to satisfy this requirement and, at the same time, to satisfy the limit imposed by the total weight of water i n the system Involves an iterative search to find the correct vapor pressure from Figure 3. A computer program was prepared for this purpose and the moisture distribution versus load was calculated for the transformer in Case 2 with a nitrogen blanket oil preservation system. (See Table I.)

Table I

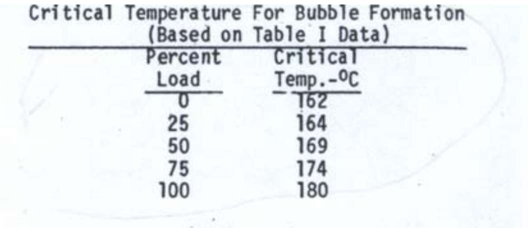
Table I Moisture Distribution Versus Load



| Percent Load | Cond. H.S. Temp. °C | Avg. Wndg. Temp. °C | Avg. Oil Temp. °C | Percent Moisture | | |
|---|---|---|---|---|---|---|
| | | | | A | B | C |
| 0 | 34 | 34 | 34 | 0.50 | 0.50 | 0.50 |
| 25 | 38 | 37 | 36 | 0.46 | 0.48 | 0.50 |
| 50 | 51 | 47 | 42 | 0.34 | 0.41 | 0.52 |
| 75 | 71 | 64 | 53 | 0.23 | 0.32 | 0.54 |
| 100 | 100 | 87 | 68 | 0.13 | 0.24 | 0.56 |

The hottest spot conductor insulation has a higher moisture content when starting from a low stabilized load, which makes it more prone to bubble evolution when the load is increased. On the other hand, the lower nitrogen concentration in the oil under this condition would make it less prone. The result of the combination of these two effects shown in Table II, where the critical temperature bubble formation has been calculated for each stabilized loading condition in Table I.

Table II



Critical Temperature For Bubble Formation
(Based on Table I Data)

| Percent Load | Critical Temp.-°C |
|---|---|
| 0 | 162 |
| 25 | 164 |
| 50 | 169 |
| 75 | 174 |
| 100 | 180 |

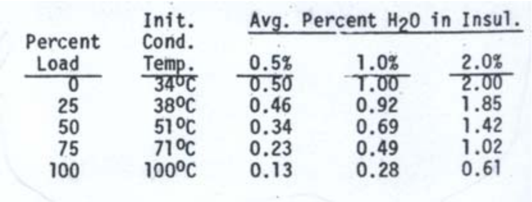
It is interesting to note that, although average moisture content of the insulation is 0,5%, the insulation near the hottest spot conductor al has less than 0.5% under load. Moisture has m from the warmer insulation regions, "A" and "B" the cooler Insulation region, "C". The result that the critical temperature for bubble formation full load is elevated from the 133°C for Case 2 180°C.

Even at lesser loads with moisture content the conductor closer to *0.5%,* the critical temperature remains relatively high, because of the lower nitrogen content in the local oil at the lower critical insulation temperature. Thus Table I indicates that a new, dry transformer is immune to bubble formation up to relatively high hottest spot conductor temperatures.

The effect of increased moisture in older Trans formers ca n also be examined on the basis of uniform moisture distribution. Table III extends Table I for moisture content in region "A" (hot spot conductor Insulation) at two higher average moisture levels for the total transformer and variation stabilized load level. Table IV lists the new critical temperatures for bubble formation corresponding to the load and moisture levels of Table III.

Table III

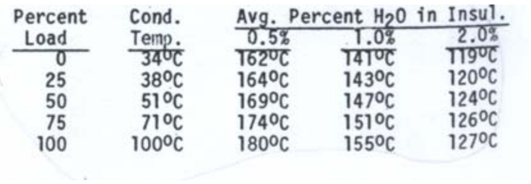
Stabilized Percent Moisture in Region “A” Insulation



| Percent Load | Init. Cond. Temp. | Avg. Percent $H_2O$ in Insul. 0.5% | 1.0% | 2.0% |
|---|---|---|---|---|
| 0 | 34°C | 0.50 | 1.00 | 2.00 |
| 25 | 38°C | 0.46 | 0.92 | 1.85 |
| 50 | 51°C | 0.34 | 0.69 | 1.42 |
| 75 | 71°C | 0.23 | 0.49 | 1.02 |
| 100 | 100°C | 0.13 | 0.28 | 0.61 |

Table IV

Critical Temperature For Bubble Formation



| Percent Load | Cond. Temp. | Avg. Percent $H_2O$ in Insul. 0.5% | 1.0% | 2.0% |
|---|---|---|---|---|
| 0 | 34°C | 162°C | 141°C | 119°C |
| 25 | 38°C | 164°C | 143°C | 120°C |
| 50 | 51°C | 169°C | 147°C | 124°C |
| 75 | 71°C | 174°C | 151°C | 126°C |
| 100 | 100°C | 180°C | 155°C | 127°C |

Bubble formation is still a concern for transformers having moderate to high average moisture content in the insulation, if a gas blanket oil preservation system is employed.

### Case 7. Effect Of Other Dissolved Gases

Even a healthy transformer has some dissolved gas other than nitrogen in the oil under normal operating conditions. Each additional dissolved gas will exert a partial pressure which contributes to the total "escaping tendency" which must be balanced against the static pressure. Other gases may be treated in the same fashion as the dissolved nitrogen.

Consider Case 5 in which a transformer with a constant pressure membrane-type oil preservation system and 0,5%moisture at the hottest spot conductor had a critical temperature for bubble formation of 176°C. The following concentrations of gases are assumed to be dissolved in the oil, in addition to the 50,000 ppm by volume of nitrogen from Case 5.

Oxygen - 1000 ppm
Carbon Dioxide - 700 ppm
Carbon Monoxide - 100 ppm

Their combined partial pressures amount to less than 7 mm Hg near the critical temperature. This is insufficient to change the critical temperature by even one degree.

### Case 8. Effect Of Thermal Decomposition Gases

Other gases must be considered from another point of view as well; namely, the generation of these gases in the local oil at the conductor hottest spot as a result of thermal degradation of cellulose during an overload. Rates of gas evolution from heated Kraft paper in the temperature range of in-terest are available in reference 12. The extent to which these gases contribute to the total "escaping tendency" in the loaded transformer can be calculated by returning to the mathematical model.

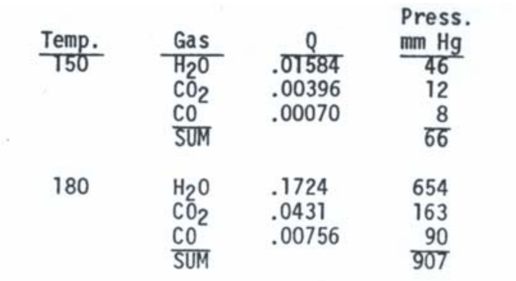
Each gram of conductor insulation in the inner wrap Is impregnated with approximately 0.5 gram of oil. If the rate of gas generation is defined as Q (cm3 NTP/hr/g), then each gram of paper produces Q $cm^3$ in one hour and this gas must be contained in $0.56cm^3$ of oil. The volume concentration of gas in oil is then:

$$C^{i} = (Q/0.56)\mathrm{xl}0^{6} = 1.8\ Q\ \mathrm{x}10^{6}\ \text{ppm} \qquad (8)$$

Equation (1), with values of K-j from Figure 2, then permits the calculation of the partial pressure exerted by each of the gases generated in one hour at the hottest spot temperature.

Reference 12 contains no data on rates of water generation, but Flowers[13] suggests that these rates are approximately four times the rates for C02 evolution. The calculation of the partial pressure of water vapor may be handled in the same fashion as the other gases. Partial pressures of the thermally evolved gases have been calculated by the method described above for two conductor temperatures.
( See Table V.)

Table V
Partial Pressures of Thermally Evolved Gases



| Temp. | Gas | Q | Press. mm Hg |
|---|---|---|---|
| 150 | $H_2O$ | .01584 | 46 |
| | $CO_2$ | .00396 | 12 |
| | CO | .00070 | 8 |
| | SUM | | 66 |
| 180 | $H_2O$ | .1724 | 654 |
| | $CO_2$ | .0431 | 163 |
| | CO | .00756 | 90 |
| | SUM | | 907 |

(Turn insulation in modern power transformers is thermally upgraded. Rate constants are not available for upgraded paper, but it is generally held to be more resistant to thermal degradation than plain Kraft paper by at least 10°C. The partial pressures given above may then be higher than those in actual transformer insulation by a factor of two or so.)

The sum of partial pressures at 150°C may be compared to the 180 mm Hg exerted by the adsorbed 0.5% moisture in the insulation in Case 2. The extra contribution from the decomposition gases is modest, but it has negligible effect at the critical temperature of 133°C. However, at 180°C the sum of partial pressures of the decomposition gases is greater than the partial pressure from 0.5% adsorbed moisture and will obviously play an important role in bubble evolution. Returning to the Case 5 example, addition of the decomposition gases lowers the critical temperature from 176°C to 163°C. As a general rule, it appears that the decomposition gases should be considered at temperatures of 150°C and above, but not at lower temperatures.

## CORRELATION WITH EXPERIMENTAL RESULTS

Initial bubble observations by Heinrichs[5] were made on a laboratory model consisting of a metal heating element with a single thickness of conductor insulation wrapped around it.

This configuration is comparable to the mathematical model described in this paper, except that there are no papers over wraps to retard diffusion of gases. Thus the mathematical model can only be expected to perform in a similar fashion for a very short time after a temperature change. The moisture content of the paper sample was not reported, but the moisture content can be inferred from the 3 ppm reported for water in oil before heating. {With the small percentage of cellulose by volume in this system, moisture content of the paper can be strongly influenced by the moisture content of the filling oil.).

If the system had stabilized at a temperature of 20°C, the 3 ppm in oil would correspond to about 2.5% moisture in the insulation. For this condition, the mathematical model would predict that temperature excursions to 100°C could produce a situation favorable for bubble formation.

This could explain the observation that preliminary heating to 100°C caused the release of a considerable quantity of "air bubbles" until the temperature stabilized. After stabilization of the model at 90°C, excursions to higher temperatures initiated bubbles at 125°C and above. This observation is consistent with the prediction in Figure 5, curve "B", if the moisture content of the insulation was as much as 0.7 percent or greater.

A second report by Heinrichs[7] gives the results of visual observations and dielectric impulse tests on winding models. Breakdown voltage at a conductor temperature of 145°C in a system previously stabilized at 90°C was only 42 percent of breakdown voltage i n the stabilized 90°C system.

It was reported that "When the conductor temperature reached 145°C, minute, pear!-like bubbles issued from the conductor insulation." Again, insulation moisture level was not recorded, but the insulation was dried by hot air and vacuum. This treatment might be expected to achieve a 0.5% moisture level in the insulation At such a level, the evolution of bubbles at 145°C is consistent with the prediction of Figure 5, curve "B".

Moisture level data is available for the insulation in physical models of winding and lead conductors for which results of thermal tests are reported in reference 6. Moisture level were in the 0.2-0.5% by weight range and the samples were held in 80°C oil whose surface was exposed to air for considerable time before testing at elevated temperatures. These conditions are also very close to those of Figure 5, curve "B", except that the gas over the oil surface was air rather than pure nitrogen.

The observation of first bubbles at temperatures from 140°C to 150°C is in reasonable agreement with the 133°C to 160°C range predicted from curve "B" for the range of moisture level in the insulation.

The conductor samples with well dried insulation. discussed above did exhibit moderate 60 Hz dielectric strength reduction at 150°C, generally in the 25-30% range, and more pronounced dielectric strength reductions at higher temperatures. However, very wet samples, with *2.9%* moisture in the insulation, showed more than a *75%* reduction in dielectric strength even at a temperature of 90°C.

While no visual observations were made on these samples, the extreme dielectric strength reduction suggests that *a* considerable quantity of gas was present in the insulation. Curve "B" of Figure 5 supports this hypothesis in that 90°C is above the critical temperature for bubble forma-tion in insulation containing 2.9% moisture.

## DI SCUSSION

The mathematical model presented in this paper has limitations because of the assumptions on which it is based, but its predictions appear to agree well with experimental experience within the scope of its applicability. The time duration of any transient event to be examined must be restricted to one hour or less, because, for longer time periods, the diffusion of gases through the outer paper wraps can significantly alter the gas concentrations in the local oil, likewise, the partial pressure of water vapor in the local oil will change as the moisture distribution moves toward a new equilibrium condition at a different conductor temperature.

Thus the model can-not be applied to long duration transient events such as the test case in reference 6 in which lead conductor models were loaded to 150°C for eight hours before dielectric stress was applied. The observed facts were that the breakdown voltage for these model s was exactly equal to the breakdown voltage for unheated models, indicating that the desorbed water vapor had diffused outward through the insulation and that the rate of evolution of degradation gases was at least balanced by the rate of diffusion of these gases.

The accuracy of predictions made by the model is further limited by the correctness of moisture equilibrium data and gas evolution rates for paper insulation, and the Henry's Law constants for the gases of concern in transformer oil. Each of these subjects will be discussed individually.

Piper's chart is *a* generalization constructed from a rather meager data base, and there is little information in the range of temperatures of interest for transformer overloading. It was necessary to extrapolate Piper's curves for the purposes of this paper. However, other observations confirm the general form of the relationship shown by Piper . A modification of the Piper chart influenced by some additional data obtained by General Electric has been presented as a nomogram[14].

When the Case 4 conditions are recalculated using that nomogram, the curve labeled B' in Figure 5 results. This confírms the thesis of low temperature bubble evolution from desorbed water, but with a discrepancy of as much as 15 degrees in critical temperature between curves B and B$^1$.

The documented data on both moisture equilibrium and gas evolution rates were determined for Kraft paper without thermal upgrading. It is likely that moisture equilibrium data does not differ greatly for thermally upgraded material. However, gas evolution rates probably are different. Degradation of *the* physical properties of upgraded paper is slower than that of plain Kraft paper and it has been shown that gas evolution and physical property changes parallel each other[12]. This implies that the rate of gas evolution from thermally upgraded cellulose common used today in power transformers would be less than the rates documented in reference 12, probably by factor of two or more. The effect of such a chance would be to de-emphasize the role played by thermal degradation gases.

A very extended temperature extrapolation available Henry's Law constants was necessary treat transformer overload conditions and it is not certain that this is justified. Measurement data was limited to the 0°C - 80°C range. The straight line relationship shown in Figure 2 does not appear to be valid at temperatures below 25°C, and it may not be accurate above 80°C either.

*

To improve the accuracy of the predictions it this paper, it would be necessary to establish a new data base for the characteristics of papers, oils| gases and water at temperatures which could encountered during overloads.

## CONCLUSIONS

A mathematical model of a small subsystem within a transformer winding has been constructed to defined operating conditions under which free gas bubbles are likely to be evolved. The model is based on the physical characteristics of the component materials in the subsystem.

Accuracy of predictions is limited b the assumptions on which the model is based, but observations on physical models during simulated overload conditions correlate reasonably well with the performance predictions. The model has been exercised to demonstrate in quantitative terms operating situations which would result in conditions favorable for bubble evolution by each of the three recognized mechanisms. Additionally it has been used to illustrate the role played by many transformers operational and constructional variables Specific lessons derived from example calculations are:

1. The type of oil preservation system has a prime influence on the tendency for bubble evolution Replacement of an automatically regulated or sealed gas blanket system with a constant pressure system having a membrane to separate the oil from an external atmosphere not only eliminates the possibility of bubble generation from pressure excursions, but also raises critical temperature required to produce thermally evolved bubbles.

2. The moisture content of the cellulose insulation on the hottest spot conductor is also of major importance in establishing the critical temperature for bubble evolution. Increased moisture level lowers the temperature at which thermally evolved bubbles can be produced. This fact implies that service-aged transformers will more vulnerable than new transformers, because of water generated in the aging process.

3. A transformer continuously loaded at or nameplate rating has a higher critical temperature for bubble evolution during transient overloads than a lightly loaded one, because of the lower stabilized moisture level of the hottest spot conductor insulation.

4. Gases produced by thermal decomposition of cellulose only contribute significantly to bubble evolution at. Woperatures above 150°C.

It was necessary to extrapolate many of the published material characteristics into the region of transformer overload temperatures. To establish confidence in the absolute values of the quantitative directions, it would be necessary to obtain gas and later equilibrium data at higher temperatures and decomposition data on thermally upgraded paper.

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.

## Discussion

**F- W. Heinrichs** (Power Systems Group, McGraw-Edison Co., Canonsburg, PA): The authors have presented an interesting qualitative evaluation of the behavior of nitrogen and adsorbed moisture according to classical gas laws affected by specific transformer operating conditions.

The authors' model (Fig. 1) is nearly identical to the model presented at the EPRI workshop on Transformer Loss of Life in Monterrey, CA, on November 28, 29, 1979 (Discussion Ref. 1). This model was also exercised through overload temperature excursions. The authors also agree that the the sites of hotspot gas bubbling are the minute oil volumes at the highly stressed corners of the transformer hot-spot conductor surrounded by paper, which acts as both a gas producing source, and a barrier which isolates the bubble generating sites from the rest of the transformer environment.

There are also several differences. The authors have not included in all cases the effects of all of the gases which can contribute to bubble formation, omitting the decomposition gases CO, CO2 , and water vapor; substituting instead adsorbed water vapor and nitrogen.

Was it the in-tention of the authors to overlook the possibility that the thermal decomposition mechanism which they accept at 150 C (Conclusion 4 of the paper) could also produce gas bubbles at a lower temperature in view of many simplifying assumptions, and the absence of tolerances in their calculations of equilibrium equations?

It is acceptable in a simplified model to eliminate some of the tedious calculations involved in a 5-element gas equilibrium expression, with the qualification, of course, that each gaseous component behaves in a system as though it existed alone. The gas laws by which the authors calculate a nitrogen/adsorbed water equilibrium were applied in the discusser's model for decomposition gases within the time and temperature constraints of the transformer loading event and indicated that decomposition gases alone will exceed saturation levels and produce minute gas bubbles of the size required to support discharges, temporal growth, and eventually premature breakdown of the dielectric systems to which they belong. The transformer model (author's Ref. 7) confirmed this.

It is noted under Assumption No. 5 of the present paper that the Henry's Law constant for water in oil at 25 C was not corrected for volume concentration, which should be 1727 parts per million per atmosphere. In this connection, it seems that the location of the Henry's constant line for water in Fig. 2 does not agree with the calculated values indicated in Assumption No. 5.

One might question the authors' assumption of equilibrium prior to the application of their model to various transformer operating conditions, particularly in view of the long diffusion times reported in the literature for water vapor. Both the authors and this discusser have observed gas bubble reduction of dielectric Strength at the conductor generating site within 15 to 30 minutes after a temperature increase. Yet it is safe to assume that the generating site is sealed from the rest of the system by the outer wraps so that moisture and gases cannot diffuse in or out of the "Local" oil space. But with a moisture content of 0.5% to 0.7% in the inner wrap, the oil space will very quickly equilibrate at that humidity. If this generating site is truly isolated, is it not reasonable in the authors' view that the equilibrium there will not be affected in 30 minutes by external conditions and must therefore rely on self-generated gases to produce the bubbling and dielectric Strength reduction observed?

The authors have now introduced nitrogen content to this subject, raising implications on equipment in the field. Beginning with the same total moisture content and both residual and generated gases in the gas generating site. How would the authors compare the gassing potential of a low pressure nitrogen system with a membrane seal system, say after five and ten years of operation?

This comparison should take into ac-count the escape of decomposition water and gases, and adsorbed water from the nitrogen system in contrast with the retention by the membrane system of all decomposition and absorbed gases, including 20,000 to 30,000 **PPM** of nitrogen commonly found in operating membrane systems.

This request represents more than just jogging the authors' equilibrium model, but in view of the implications of conclusions l, 2, and 3 on the integrity of the units in service, transformer users are certain to want a better understanding of their exposure to the dielectric effects of both systems.

Is it the authors' position that the equilibrium calculation for only nitrogen and adsorbed water vapor are adequate for specifiying new maximum hot-spot conductor temperatures in our loading standards throughout the temperature range to 180°C?

In conclusion, this discussion presents an opportunity to reiterate a previous recommendation on the inadvisability of postponing the reduction of the maximum allowable hot-spot conductor temperature levels in our loading standards pending a consensus among investigators upon the true gassing mechanism.

## REFERENCE

1. **F. W. Heinrichs**, "Gás Bubbles Generated by Hot-Spot Winding Temperature and their Effect on Transformer Insulation and Life," Presented at the EPRI Electrical Systems Division Transmission Substation program on Transformer Loss of Life, Nov. 28, 29, 1979, Monterrey, CA.

Manuscript received August l, 1984.

**H. Okubo and Y. Taniguchi** (Toshiba Corp., Kawasaki, Japan): We would like to commend the authors for the contribution in providing a valuable technique for solving the condition of bubble formation in oil-immersed transformer. However we would like to comment on the following points:

*(1) Membrane seal type conservator.* Even if we use membrane seal type conservator instead of N2 blanket gas type, several gases will permeate the membrane over a period of time and the N2 concentration will be about its saturation level, after 20 to 30 years. In this case, static pressure on the liquid surface $p^{STAT}$ is always almost constant and is = 760mmHg. Therefore, the bubble formation critical temperature may be lower than the case with N2 blanket gas type .In addition, the influence of material degradation after 20 to 30 years will not be ignored.

*(2) Influence of gravitational force.* Hydrostatic pressure for oil is ca. 68mmHg at l meter below liquid surface. However, as was written as Case 2 in your paper, the bubble was formed 6.7% High pressure (76mmHg) than $p^{STAT}$ static pressure on the liquid surface P (110mmHg), and this 6.7% unbalance pressure (76mmHg) can be considered comparable value with hydrostatic pressure (68mmHg).
We think we should take the influence of hydrostatic pressure in consideration for pressure evaluation with actual transformer and determine the least critical unbalance pressure between partial pressure and static blanket gas pressure.

*(3) Bubble formation and dielectric characteristics.* You have compared the visible bubble formation to dielectric breakdown characteristics. We think you had better take PDIV (Partial Discharge Inception Voltage) instead of BDV (Breakdown Voltage) for comparison, because PDIV depends highly on bubble formation and BDV is influenced by the dielectric strength of paper itself.

We would be grateful if you would show the experimental data with which you measured and compared the PDIV to visible bubble formation and, in this case, how is the PD magnitude (in $p^C$)?

*(4) Bubble generation.* What is the diameter of visible bubbles and what is the bubble shape between paper barriers? In any case, bubble formation will be influenced by the thickness of paper covering of turn conductor. From this point of view, the visible bubble formation temperature will not always be the same as the temperature at which the small bubble will be formed at the portion adjacent to conductor.

Manuscript received August l, 1984.

W. J. McNutt, T. O. Rouse, and G. H. Kaufmann: The authors wish to thank the discussers for the interest they have shown and for the new perspectives they have brought to our subject.

While Mr. Heinrichs gives us credit only for "an interesting qualitative evaluation", we believe that the correlation between the quantitative predictions of our model and the physical facts observed by experimenters is more than coincidence.

Mr. Heinrichs suggests that he had previously proposed a similar model at an EPRI workshop in 1979. Review of the Minutes of that workshop show that Mr. Heinrichs discussed a physical model involving "an oil space at the overlap of the conductor tape." However, Mr. Heinrichs limited his consideration to "the decomposition of cellulose into its constituents CO, CO2 and H2O giving rise to gases that collect in the oil space at the edge of the taping." Other than a table of rates of generation of thermal decomposition gases, no data nor calculations related to bubble formation mechanisms were furnished which could define critical operating temperature for a transformer.

On the other hand, the present paper considers all of the gas sources which can contribute to the formation of bubbles and provides a method for evaluating the likelihood of bubble generation.

We greatly appreciate Mr. Heinrichs observation on the conflict between Assumption no. 5 and Fig. 2. Checking our data we find that the units for the example value of K = 1940 in Assumption no. 5 should have been ppm by weight/atm, which becomes 2992 ppm by vol(NPT)/atm at 25 °C. We also found that the H2O line on Fig. 2 was incorrectly plotted. Readers may correct the H2O curve by connecting the point K = 2992 ppm vol (NPT)/atm 25 °C to a point K = 569 ppm vol (NPT)/atm at 180°C. AH of the calculations involved in the paper were performed using a computer program which contained the correct Henry's Law Constants for water.

This paper was presented in a tutorial vein to illustrate the specific role played by each operating variable. Thus Case 2 demonstrates the partial pressure contributions of water vapor and nitrogen at temperatures where thermal decomposition gases make a very small contribution. We did not intend to imply that thermal decomposition gases could be ignored, but rather that they play a very minor role at temperatures below 150°C.

Likewise we did not intend to exclude the hydrostatic pressure created by a head of oil over the bubble evolution site. This factor was mentioned on the first page of the text, but was not considered in the example cases because it was felt that the fashion in which it could be included was obvious. One further example case in which all factors are acting simultaneously would clarify the situation and will be given here.

*Case9. Comparison Of Critical Temperatures For Gas Cushion And Membrane Conservator Oil Preservation Systems.*

Consider two identical transformers being overloaded to a given hot-spot temperature for a period of one hour following stabilized loading at a hot-spot temperature of 80 °C, with the hot-spot location l .5 meters under the oil surface.

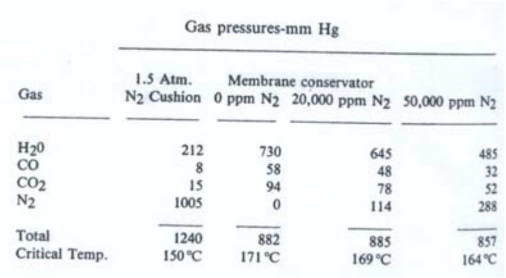
One transformer has a 1.5 atmosphere nitrogen cushion oil preservation system and the other has a membrane conservator system. The second unit will have no dissolved nitrogen in the oil initially, but after ten years may have 20,000 ppm and after 25 years may have 50,000 ppm. (Our experience does not confirm the comment by Okubo/Taniguchi that the oil will become saturated with nitrogen after 20-30 years.)

A critical temperature for bubble formation will be reached in the conservator unit when the summation of partial pressures exceeds 860 mm Hg (760 mm of atmospheric pressure plus 100 mm for the static head of oil). The total static pressure to be overcome in the gas cushion system is 1240 mm Hg. A number of possible operating conditions have been considered to draw the family of curves shown in Fig. A.

Table A illustrates the partial pressure contributions of each gas at the critical temperature for both systems at an insulation moisture con-tent of 0.5%. It can be seen that nitrogen makes the largest contribution to potential bubble formation for the gas cushion system, while water vapor makes the largest contribution (at higher critical temperatures) in the membrane conservator system.

TABLE A

Gas partial pressures at the critical temperature insulation moisture content = 0.5%



| | Gas pressures-mm Hg | | | |
|---|---|---|---|---|
| | 1.5 Atm. | Membrane conservator | | |
| Gas | $N_2$ Cushion | 0 ppm $N_2$ | 20,000 ppm $N_2$ | 50,000 ppm $N_2$ |
| $H_20$ | 212 | 730 | 645 | 485 |
| CO | 8 | 58 | 48 | 32 |
| $CO_2$ | 15 | 94 | 78 | 52 |
| $N_2$ | 1005 | 0 | 114 | 288 |
| Total | 1240 | 882 | 885 | 857 |
| Critical Temp. | 150 °C | 171 °C | 169 °C | 164 °C |

Fig. A provides an answer to Mr. Heinrichs question on comparison of oil preservation systems, assuming the same insulation moisture content in each. Mr. Heinrichs implies that the gas cushion system will purge the transformer of moisture and decomposition gases, but we know of no documented evidence of the degree to which this occurs. Moisture content of the insulation and dissolved gas content in the oil tends to build up with time in all transformers.

If the degree in buildup is known or can be inferred from measurements, that information can be taken into account in the bubble evolution calculation. Fig. A also addresses the question of limiting safe hot-spot temperature. Whether bubbles will be formed at 180 °C or not is function of the time at 180 "C. In a variation of the Case 9 example it was determined that bubbles could be formed in the gas cushion transformer just by raising the temperature to 180 "C.

However, in the membrane conservator transformer with 50,000 ppm of nitrogen in the oil, the temperature could be at 180°C for about 5 minutes before conditions for bubbling would be reached. In either event, the model indicates that 180°C operation can be risky.

In order to apply the mathematical model it is necessary to make some assumption about the moisture and gas content in the local oil at the hot-spot location before the overload is applied. As Mr. Heinrichs points out, most operating transformers seldom reach a true equilibrium condition. However, some reasonable equivalent of equilibrium can be inferred from previous thermal history to establish the initial conditions,of a range conditions can be explored.

We agree with Mr. Heinrichs that whatever moisture and gas levels exist in the local oil in-^"will be trapped there during the thermal excursion. Therefore,.they will contribute to the summation of partial pressures tending to form Bubbles,*in addition to* the partial pressures generated by thermal decomposition gases. This effect can be seen in Table A.

The questions on observation of visible bubbles in the Okubo/Tanaguchi discussion do not pertain to material presented in this paper so we offer no response here, other than to say that we do believe ^ t the first free gas will be present in the local oil at the conductor r some time before visible bubbles will emerge from the paper. At higher temperatures, where the summation of partial pressures is far in excess the static pressure, the time for visible bubble emergence will decrease.

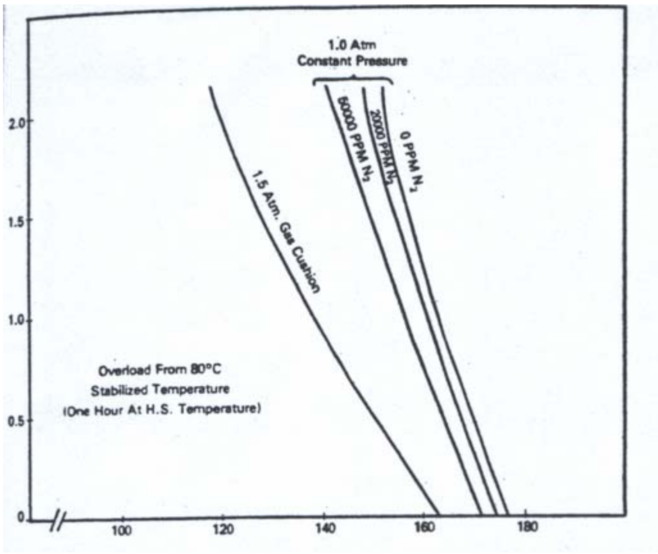


Fig. A Critical hot spot temperature above which conditions are favorable for bubble formation with two types of oil preservation system.

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