Bubble Evolution from Transformer Overload

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Abstract: Bubble evolution from overloading of transformers is a concern due to possible dielectric failure. Since overloading is inevitable for short periods during peak demand periods, it is necessary to specify the limits of overloading with respect to winding hot spot temperature which determines bubble evolution. Through extensive coil model testing in the early 1990s, a mathematical equation was formulated to compute bubble evolution temperatures under a variety of conditions: moisture in insulation, gas content of oil, and the pressure in the system. This paper describes the coil models, test results and the mathematical formula. Also presented is a tentative mechanism of bubble formation.
Keywords: Transformer, bubble, overload

I. INTRODUCTION

A new bubble generation model developed under EPRI project 1289-3 and outlined in EPRI reports EL-6761 and EL-7281 in March 1990 and March 1992 respectively is the basis for the revision of Annex A of C57.91-1995 [1-3]. The new model used realistic coil segments to produce bubbles under overload conditions. An earlier model that had been developed purely from physico-chemical consideration regarding bubble generation based on vapor pressure computations and the gas content of oil was used for the development of Annex A cited above, based on EPRI Report EL-5384 [4]. It had been assumed in that model that the condition for generation of a bubble was that the total gas/vapor pressure contribution exceed the external pressure exerted on the bubble. The total gas/vapor pressure contribution was computed from the gas content of the bubble(from mostly dissolved nitrogen and some generated gases) and from water vapor released by heat from paper insulation in contact with the hot conductor. The bubbles in an initially degassed system (as in sealed transformers with conservators) would mostly consist of water vapor. It was argued that in a nitrogen saturated system, the bubbles would contain mostly nitrogen, and the balance would be from water vapor and generated gases. These assumptions led to the conclusion that in a gas saturated system bubbles would be formed much earlier than in a conservator system because only a small increase in temperature would be needed to release sufficient water vapor. It was estimated that the bubble evolution temperature in a gas saturated system would be as much as 50^{o}C lower than the bubble evolution temperature in a conservator system.

A complete re-evaluation of the basic assumptions and experimental methods to verify bubble evolution was conducted in the new study. The significant findings are given below.

II. COIL MODEL STUDY

Test Setup

Two coil models used are shown in Figs. 1A and 1B. The first coil model had three discs, and used thermocouple leads to measure hot spot temperature in the winding, and bubble evolution had to be observed visually. The second model had only one disc, but used fiberoptic temperature sensor (Luxtron Model 750) in place of thermocouple sensor to sense hot spot temperature, and a separate winding was used to apply voltage for PD detection of bubbles in addition to visual observation. Moisture content of the paper in the coil and gas content of the oil were changed over a wide range. Moisture ranged from 0.3% to 8.0% (dry/oil free basis), and gas content, from nearly fully degassed to (nitrogen) saturated.

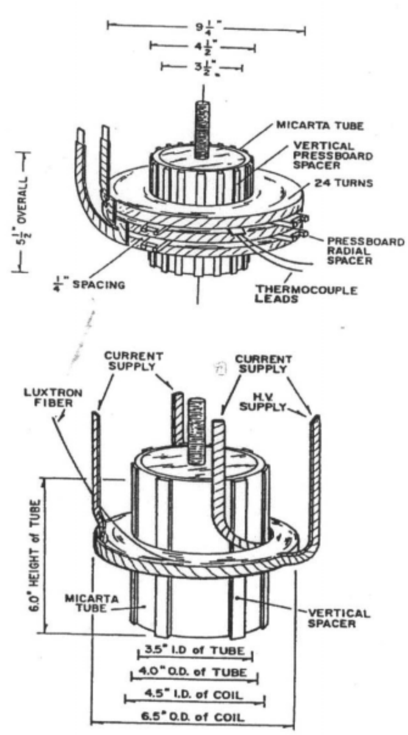

Fig. 1A. Coil Models: Sketch

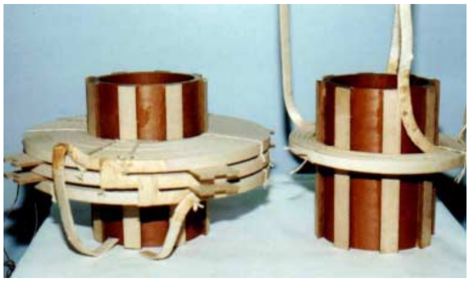

Fig. 1B. Coil Models, Photo

Figs. 2A and 2B show the test tank used. The glass tank enabled visual observation of bubble formation. The same tank was used for both types of coils, and for gas blanketed and conservator systems.

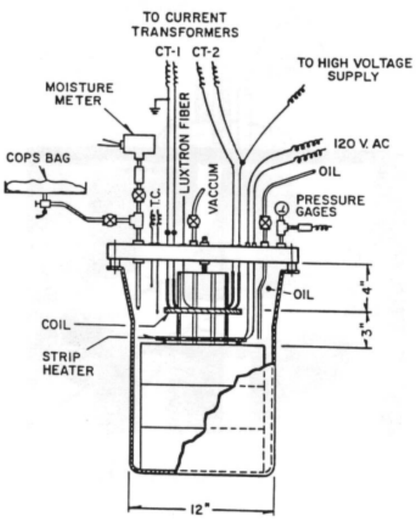

Fig. 2A. Test Tank, Schematic

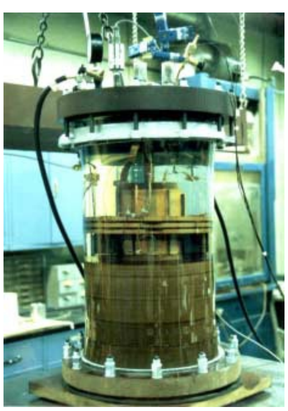

Fig. 2B. Test Tanks, Photo

The full test assembly is shown schematically in Fig. 3 which included the test tank, H.V. transformer, two current transformers, voltage regulators and PD detection oscilloscope.

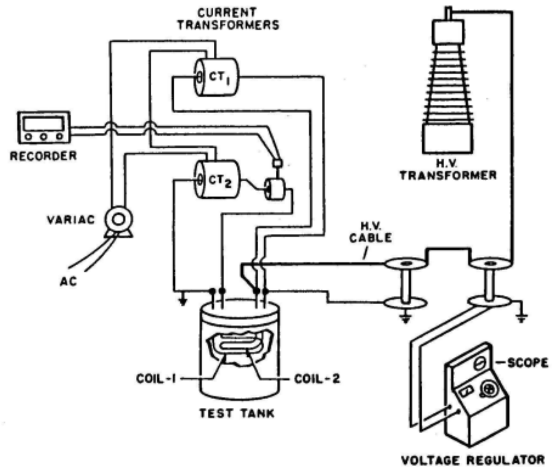

Fig. 3. Full Test Assembly

Time constants for the coil and oil were determined by separate overload runs at lower current load than used in actual overload tests. The parameters related to these overload runs are given in Table 1.

Table 1. Parameters on Overload Runs

Initially stabilized temperature	:	55°C (75°C*)
Increase in hot spot rise over oil	:	65 °C
Top oil rise/ambient	:	240 °C
Ultimate hot spot temperature	:	360 °C
Coil time constant	:	12 minutes
Oil rise time constant	:	120 min
Load duration	:	30 min
Static head of oil	:	4 in (6.5 torr)

*for 3-disk model tests

A total of 26 model tests were conducted, of which 12 were using the 3-disk model and the remaining, the single disk model. Both gas blanketed and conservator systems were tested. The moisture content of the paper in the coils ranged from 0.3% to 8.0%, and the nitrogen gas content, from 0.45% to 12.3% A tabulation of the test model variables is given in Table 2.

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Table 2. Model Test Variables

#	System	Moisture in paper ,% W	Gas in oil, % g
	3-Disk Tests		
1	C*	0.3	0.45
2C	0.3	1.48	
3C	0.6	8.15	
4	GS**	0.5	9.95
5	GS	0.4	9.68
6	GS	0.4	11.0
7	GS	0.4	12.3
8	C	1.5	1.9
9	GS	1.1	9.7
10	GS	2.3	9.7
11	C	1.6	1.56
12	GS	1.6	9.73
	Single Disk Tests		
13	GS	1.0	8.8
14	GS	4.0	8.8
15	C	3.0	1.0
16	C	3.0	1.0
17	C	8.0	1.0
18	C	8.0	7.7
19	C	8.0	8.8
20	C	4.1	1.0
21	C	5.7	1.0
22	GS	5.9	8.8
23	GS	3.1	8.8
24	GS	5.3	8.8
25	GS	7.8	8.8
26	GS	2.8	8.8

* Conservator ** Gas Space

The total pressure could be computed by adding the water vapor pressure corresponding to the moisture content, and the gas pressure corresponding to the gas content. The water vapor pressure is computed from

$$\text{Ln } P = 22.454 + 1.4495 \ln W - 6996.7/T \qquad \text{(Eq. 1)}$$

where P is the water vapor pressure (in torr or mm Hg), W is the water content (%), and T is the temperature (°K) at which bubbles were formed. The gas pressure P_g is computed from

$$P_g = (g/S) \times P_{amb} \qquad \text{(Eq.2)}$$

where S is gas solubility (%) at the temperature of the oil and P_{amb} is the ambient atmospheric pressure in torr.

The solubility of nitrogen in oil as a function of temperature $T(^oK)$ is given by:

$$\text{Log } S = -\frac{112.9}{T} + 1.325 \qquad \text{(Eq. 3)}$$

To get the total pressure, the static head of oil should also be added.

Test Results

The detailed test results are given in the references cited above. Therefore, the results presented here are mostly graphical and pictorial.

Fig. 4 shows photos taken of bubble generation from the coils, both the three disk and the single disk models. The pictures show bubbles rising from the coil and collecting underneath at high moisture and gas levels. At low moisture and gas levels bubble generation was less spectacular and less profuse.

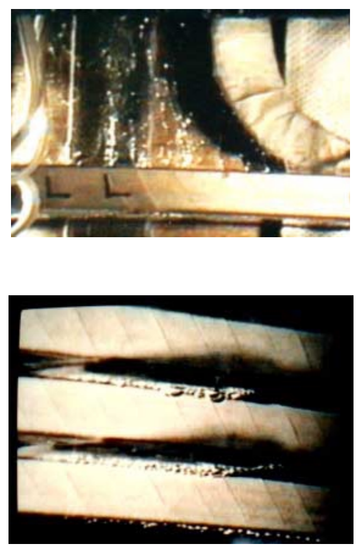


Fig. 4. Bubble Generation in Coils, Photos

Fig. 5 shows temperature rise in the winding and in the oil, as well as the point of bubble generation in a particular experiment using the single disk model. The zig-zag after the point of bubble generation monitored by the fiberoptic sensor is due to the gas pocket around the sensor head. The rapid temperature rise simulates the conditions in a transformer winding under overload conditions. For the 3-disk model, the formation of bubbles was visually observed.

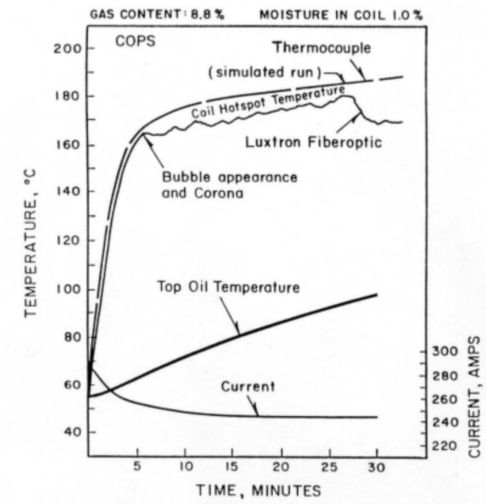


Fig. 5. Temperature Rise and Bubble Generation

Fig. 6 shows the results in graphical form for totally gas saturated and degassed systems. The upper curve corresponds to degassed oil, and the lower curve, to gas saturated oil.

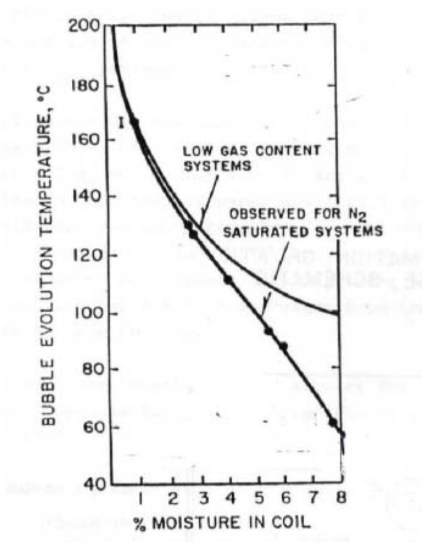


Fig. 6. Bubble Evolution Temperature Chart

It is obvious that at low moisture values the bubble evolution temperature is virtually the same for degassed and gas saturated systems. The previous model [4] had predicted a 50°C difference. Only at high moisture levels there would be a significant influence from the gas content. It will also be noticed that for a dry transformer the bubble evolution temperature would be so high that it may not be reeached during the overload to generate bubbles.

A more detailed discussion of the full test results will be given in the next section.

III. MATHEMATICAL FORMULATION

Mathematical Formula

There are three variables, water content of the paper (W), gas content of the oil (g) and total pressure (P) that influence bubble evolution temperature (T). In Fig. 6 these variables are included except that intermediate gas level data points are not shown. The shape of the curves imply that no simple mathematical formula would represent all the experimental data. A breakthrough came when it was realized that the upper curve, representing degassed systems, could be represented by a form of the well known Piper Chart relationship which relates water vapor pressure to water of paper and temperature already given in Eq. 1. When we rearrange the equation in terms of T, we get:

$$T = [6996.7/22.454 + 1.4495 \ln W - \ln P] \qquad \text{(Eq. 4)}$$

This gives indication that the bubble consists purely of water vapor, though the above exact fit cannot be explained well.

To lower curve in Fig. 6 could be obtained by subtracting an exponential term, exp (0.473W) to fit the data points on that curve.

The final part, to include varying gas contents, is a power term combined with the exponential term, $(g/30)^{1.585}$, again to fit experimental data. The final empirical formula is:

$$T = [6996.7/22.454 + 1.4495 \ln W - \ln P] - [\exp(0.473W) \times (g/30)^{1.585}] \qquad \text{(Eq. 5)}$$

While it is difficult to explain the formula on a theoretical basis, it adequately describes the bubble evolution temperature in all the model tests, as Table 3 shows.

Table 3

Observed and Predicted Bubble Evolution Temperatures

Test #	Observed °C	Predicted °C
1	220	224
2	215	215
3	209	191
4	209	192
5	204	209
6	209	209
7	211	208
8	158	153
9	160	164
10	131	134
11	152	151
12	158	149
13	166	168
14	110	113
15	130	130
16	109	111
17	99	98

(Table 3, Continued)

18	60	64
19	55	53
20	122	119
21	110	108
22	90	91
23	128	124
24	93	98
25	60	58
26	132	128

The agreement between the observed and predicted temperatures is remarkable. T few degrees difference may be attributed to inaccuracies in observing bubble evolution temperatures and to the mathematical fit.

The prior mathematical model (3,4) predicted significantly lower bubble evolution temperatures (as much as 50^{o}C) for gas saturated models as Table 4 reveals (for tests 1-12):

Table 4

Comparison of Present and Prior Models
A. Gas Space Systems

Test #	Computed, ^{o}C Present Model	Prior Model
3	191	153
4	192	143
5	209	154
6	209	161
7	208	165
9	164	110
10	134	87
12	149	98

B. Conservator Systems

1	220	224
2	224	212
8	158	151
11	151	149

The significant deviation for gas space systems is due to the undue weight given to dissolved gas content to bubble internal pressure in the prior model. For conservator systems, the dissolved gas content is low in the examples given. The prior model was based on the assumption that the total pressure in the bubble from gases and vapor should just exceed the external pressure to form a bubble, and the total pressure was computed from gas content of the oil, water vapor generated by heat, and generated gases (a minor component). Eq. 1 above would give the water vapor pressure, and the gas content of the oil would be added to this pressure, along with generated gases (of decomposition). The new mathematical formula does not give equal importance to the dissolved gases as the prior model. Justification for this will be given below.

Mechanism of Bubble Formation

As mentioned above, the prior mathematical model had used a simple principle for bubble formation:

$$P_{int} = P_{ext} \qquad \text{(Eq. 4)}$$

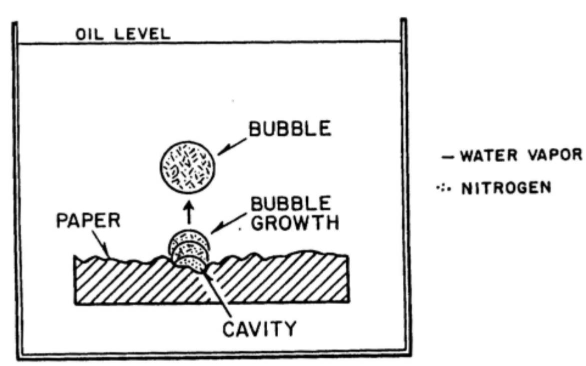
where P_{ext} and P_{int} are the external and internal pressures. Strictly, the first term should slightly exceed the second for bubble formation.

The above formula for bubble formation misses an important term, the surface tension pressure [5]:

$$P_{int} = P_{ext} + 2\sigma/R \qquad \text{(Eq. 5)}$$

where σ is the surface tension and R is the bubble radius. What this implies is that if a large bubble starts from a tiny bubble, R would be very small, and the second term would be very large, and the total external pressure would be so large as to collapse the micro-bubble. Bubble dynamics experts agree that a free bubble is not formed inside the fluid, but is always generated in a cavity on the walls of the container or a solid surface.

For the overload condition, we may visualize the situation as follows: there is an initial cavity on the insulation paper (actually many cavities) filled with some water vapor and dissolved gases. During overload the temperature of the paper, and of the cavity increases rapidly, and the cavity would expand, at the same time getting more water vapor from the paper driven out by the overload temperature. Finally the cavity would be large enough and the energy sufficient to release a free bubble. Note that during this process the dissolved gas in the bulk oil does not get time to diffuse into the bubble, though some of the dissolved gas would be expected in the bubble, whose quantity cannot be theoretically predicted. The formation of the bubble is schematically shown in Fig. 7.



(Fig. 7. Bubble Formation, Schematic

It is now obvious that a simple mathematical formula cannot be formulated to predict bubble evolution temperature.

Application to Transformers

Some examples are given below to illustrate how the bubble evolution hot spot temperature can be computed in the transformer situation.

Example 1

Data:
External pressure = 750 torr
Oil depth(8 ft) pressure = 176 torr
Water in paper* (W) = 1.2%
Gas in oil (g) =1.0%
* moisture in paper is on a dry basis

$$= \frac{\text{Moisture wt}}{\text{Wt. of dry paper}} \times 100$$

Computation:
Total pressure, P = 926 torr

From Eq. 3, we get
T = 440°K or 167°C

Example 2

Assume total pressure as in 1
W = 2.5% g = 1.0%
Hence, T = 413 °K = 140°C
(If g = 3.0%, T would drop only one degree)

Example 3

Assume total pressure as in 1
W = 0.5% g = 0.5%
Hence T = 468.6°K = 195.6°C

The curves shown in Figure 6 as well as the formula show that if the paper is very dry, below 0.5%, there is no concern about bubble generation from overload since the hot spot temperature required, about 200°C, would not be reached. The curves do show, however, that at 2.5% moisture, bubbles would be generated at 140°C. This 140°C has been cited in the literature on bubble evolution from overload without any qualification[6]. The present formula reveals that bubble evolution at this temperature would be expected only from overload of an aged transformer which may typically contain 2.5% moisture or above.

The overall impact of the mathematical formula is that it removes the fear of spontaneous bubble generation from overload of dry transformers regardless of the gas content of the oil.

IV SUMMARY

The work described above may be summarized as follows:

1. Coils models realistic of transformer windings were used in the overload study.
2. Bubble formation could be observed visually and by PD
3. Temperature at the hot spot was measured by either thermocouples or by fiberoptic sensor cables.
4. The bubble evolution temperatures were fitted on an empirical mathematical formula.
5. It appeared that the previous mathematical model had predicted much lower evolution temperatures for gas saturated models. The present model did not show significant lowering except when moisture content was excessive.
6. The mechanism of bubble formation suggests that bubbles are formed from a cavity on the surface of paper which is supplied with water vapor from the paper , causing the cavity to expand and finally release a bubble.
7. An aged transformer with moisture levels in the vicinity of two and a half percent in paper may release bubble at hot spot temperatures as low as 140°C.

V. REFERENCES

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VI. BIOGRAPHIES

T. V. Oommen (SM '91) was a Senior R & D Engineer with Westinghouse Electric Corp from 1977 to 1990, and with Asea Brown Boveri from 1991 to 2000 working on transformer related projects such as insulation life, insulating fluids, static electrification, and bubble generation, the last two being sponsored by EPRI. He is now a Consultant.

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