AN INVESTIGATION INTO THE EFFECTS OF PARTIAL DISCHARGE ACTIVITY IN SULPHURHEXAFLUORIDE GAS ON LIQUID INSULATION

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I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

(Signature of candidate)

4th day of JANUARY 1992

Abstract

The purpose of the work presented here was to investigate the effects of SF_6 gas present in insulating liquids. This research was carried out mainly by means of experimental work. Investigations involving the gas evolving or absorbing properties of air and SF_6 saturated insulating liquids were carried out. These tests showed that the liquids investigated (transformer oil and silicone liquid) were capable of absorbing large amounts of SF_6. Further experiments were performed to discover what influence this would have on stressed, enclosed liquid samples with air gaps above them. In addition to this, partial discharges in gas bubbles trapped behind paper insulation were investigated under high voltage stresses. These comparative experiments were done using SF_6 and N_2 bubbles. The results obtained have provided evidence that SF_6 present in liquid insulation is not deleterious to the insulation when compared with the presence of non electronegative gasses.

In memory of my father
Emilio Ruffini
1924 - 1989

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Chapter 1 : Introduction

The increasing use of SF_6 gas insulated equipment has led to situations where there are interfaces between gas insulated and liquid insulated high voltage equipment. An important issue to be considered in these situations is what the effects of a leak of SF_6 (which is usually maintained at pressures of between 2-4 bar) into oil or other liquid insulated equipment will have on this insulation.

There have been conflicting opinions as to whether SF_6 being mixed with insulating liquids will have deleterious consequences or not and some authors (Yamashito, 1975, 1979), (Bakale and Shmidt, 1981) have hinted at possible beneficial effects of the presence of SF_6 in transformer oil. One of the more important aims of this work was to make an attempt to reach some conclusions regarding the danger of mixing SF_6 and liquid insulation and under what conditions, if any, this mixing is acceptable.

An investigation was carried out in an attempt to clarify this issue and in particular to consider the effects of partial discharge activity in SF_6 bubbles on the insulation. It was hoped that this investigation would result in conclusions as to the conditions under which the contamination of insulating liquids with SF_6 would present the greatest danger to the insulation. Two liquid insulators were used for this investigation, these being mineral oil and silicone liquid. It was felt that since mineral oil and silicone liquid have differing chemical natures their reactions to partial discharge activity in SF_6 bubbles might be distinctly different.

A series of experiments was undertaken. The essence of this work, which was divided into three stages of experimentation, is presented in the following three chapters with each chapter discussing one of the three sets of experiments.

The gas absorbing and evolving properties of SF_6 saturated transformer oil and silicone liquid were investigated, in relation to temperature, using a set-up based on the Pirelli test apparatus described in the British Standards, BS 5795.

The second set of experiments was conducted to investigate the effects of SF_6 and air saturated insulating liquids with regard to the suppression of partial discharge activity.

The final set of experiments was undertaken to examine the partial discharge activity in trapped SF_6 and N_2 bubbles under high stress.

1.1 Background

Sulphurhexafluoride can exist in insulating liquids in two forms.

1] SF_6 gas dissolved in the oil.
2] SF_6 Gas bubbles present in the oil.

The SF_6 in the dissolved form is not perceived to be a significant danger. The large danger to the insulation is regarded as being the presence of SF_6 bubbles in the liquid, because this increases the likelihood of partial discharge activity.

A partial discharge is a discharge that bridges a portion of a dielectric. Partial discharges can be caused by localised electric fields and always occur in a gaseous or vacuous phase. (In this document partial discharges will also be referred to as corona). Since SF_6 gas bubbles in a liquid gives rise to the situation of high localised field caused by a change in dielectric coefficient at the bubble boundry, partial discharges occur in these bubbles. Many authors (Mandelcorn et al, 1984), (Kaufmann, 1983) regard partial discharge activity as being synonymous with the onset of bubble formation in dielectric liquids. Because of this the effects which increase or decrease the presence of bubbles in a highly stressed liquid will have a corresponding effect on the increase or decrease of partial discharge activity.

1.1.1 Factors influencing bubble formation in dielectric liquids

Considering the above it is necessary to look into factors which inhibit or aid bubble formation in dielectric liquids.

1.1.1.1 The effect of temperature

It has been found that temperature is the most significant parameter related to the onset and intensity of gas bubble evolution. There is general agreement that the solubility of SF_6 decreases as temperature increases and that bubbles evolve from the oil as the temperature increases. In contrast to this the solubility of air increases as temperature increases, though more gas bubbles evolve at higher temperatures than at room temperature. The relationship between air and SF_6, as far as solubility in transformer oil with respect to temperature is concerned, is shown in figure 1.1.

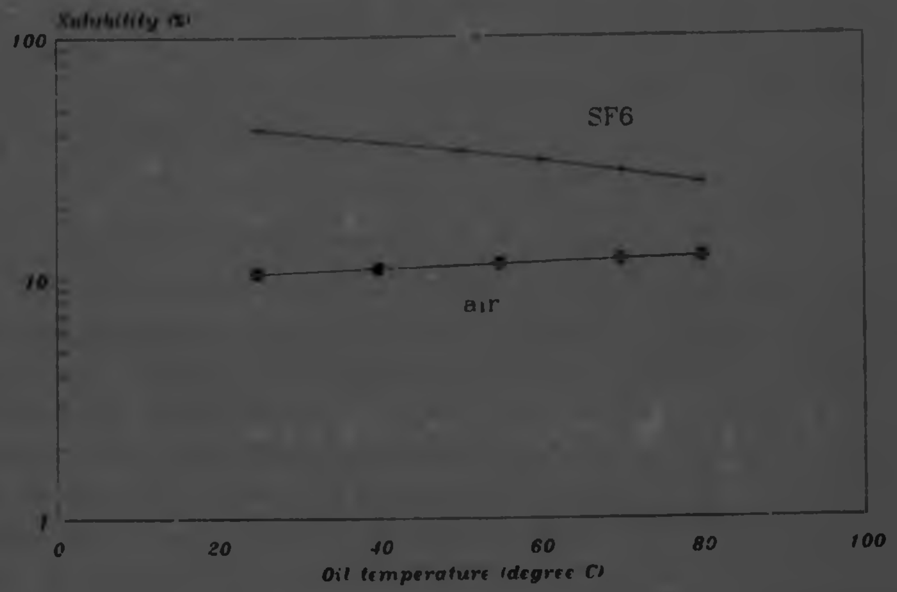


Figure - 1.1 Solubility of air vs SF_6
transformer oil
(Ref BBC publication No DTR 81-117E)

1.1.1.2 The effect of pressure

The bubble formation inside a liquid is affected by the pressure on the liquid surface (Gally, Fourmier and Senes, 1984). The higher this pressure the more difficult the formation of bubbles, therefore the pressure exerted on the liquid tends to have a positive effect on the breakdown strength of dielectric liquids. It should be noted that a high pressure on a liquid will cause it to become super-saturated. The greater quantity of gas dissolved in the liquid might result in gas being evolved from its dissolved state when the pressure is reduced.

1.1.1.3 The effect of motion

It has been found that some motion in a liquid will help dislodge trapped bubbles and that motion is likely to break up large bubbles into smaller bubbles which present a lesser chance of breakdown in a liquid dielectric. On the other hand it has been shown (Kaufmann, 1977) that if the liquid is super-saturated, agitation in this liquid will aid the evolution of gas from the dissolved state. The effect motion has on the breakdown strength depends on the speed of this motion (Ikeda et al, 1981). Up to a certain speed of agitation the effect on the strength of the liquid dielectric will be positive since the bridging of fibres and bubbles will be disrupted, but if the agitation becomes too fast the breakdown strength will be lowered since dissolved gas will be encouraged to come out of solution and form bubbles.

1.1.1.4 The effect of humidity

It has been found that under conditions of higher atmospheric humidity the moisture level in a liquid will increase. It was found (McNutt, Rouse and Kaufmann, 1985) that increased moisture levels in liquid insulation lower the temperature at which thermally evolved bubbles can be produced.

1.1.1.5 The effect of the liquid properties

Observations made (Mandelcorn et al, 1984), (Meyrueix, Petriat and Tobazeon, 1982) concerning the rate of gas evolution revealed that liquids with low viscosity and high aromicity have higher gas evolving rates than liquids in which the viscosity is higher and the aromicity lower.

1.1.1.6 The effect of high electric fields

Very high electric fields will cause bubbles to form and partial discharge activity to begin. Even if there is no gas present and the field gets high enough a vacuous phase will be formed and discharges will occur although the field strength at which partial discharges will take place will be higher than it would be if gas was present (Yamashito and Mori, 1975), (Mandelcorn et al, 1984), (Lesaint and Tobazeon, 1985).

1.1.2 Dielectric effect of SF_6 on transformer oil

A significant consideration is what effect the presence of SF_6 in transformer oil will have on partial discharge activity in the oil.

SF_6 has a high electronegativity and readily attaches electrons resulting in the formation of negative ions. The field in liquid dielectrics is usually not uniform, thus there will be a strong field near the cathode due to positive ions produced by collisions with electrons (collision ionization).

1.1.2.1 Case 1

If SF_6 is present it will capture the electrons emitted from the cathode becoming SF_6^- and these negative ions formed will neutralize the effect of the positive ions decreasing the potential gradient at the cathode.

1.1.2.2 Case 2

If there are too many SF_6^- ions present, these excess negative ions will create a steep potential gradient near the anode instituting breakdown at a reduced voltage.

1.2 Disadvantages and advantages of SF_6 gas in liquids

The behaviour of dissolved SF_6 in liquids has been investigated from two perspectives. The first is the effect that the dissolved gas will have on the electrical breakdown properties of the liquid, the second examining whether the presence of SF_6 will lead to any deleterious chemical effects.

1.2.1 Viewpoint on electrical breakdown properties

Some authors have suggested that the excellent dielectric properties of SF_6 might lead to a combination of oil and SF_6 producing a stronger dielectric in terms of an increased breakdown stress. It was found (Megahed and Tropper, 1967) that there is a slight increase in the dielectric breakdown strength in oil with SF_6 present compared to oil without SF_6. It was postulated (Bakale and Shmidt, 1981) that SF_6 dissolved in transformer oil would diffuse into the region of a developing discharge channel and quench further development of the channel. They also proposed that the high electronegativity of the SF_6

would attract and bind any free electrons existing within the liquid. Some tests were conducted (Yamashita and Amano, 1979) investigating the influence of surface pressure and the electronegative effects of enclosed samples of SF_6, iodine and argon gas and it was concluded that SF_6 seems to increase the breakdown strength of bubbles and that there will be a reduction in liquid motion and partial discharges due to surface pressure and electronegative properties exhibited by the SF_6.

It is also postulated that dissolved SF_6 in transformer oil will lead to the degradation of the dielectric breakdown stress and hence that SF_6 and transformer oil must not be mixed. The main claim of a document produced by BBC (Brown Boveri, publication No DTR 81-117E, 1981), is that dissolved SF_6 will come out of solution under conditions of temperature cycling and form bubbles within the liquid. These bubbles may discharge in high stress regions. Since hot-spots within electrical apparatus often coincide with high stress regions, the presence of SF_6 is considered undesirable. This argument is supported (Galley, Fourmier and Senes, 1984) and it is pointed out that since the oil is at atmospheric pressure, any SF_6 bubbles formed will have a far lower breakdown stress than the liquid and are therefore likely to discharge in high stress regions. None of the above authors, however, examined in detail under what conditions such bubbles of SF_6 are likely to form.

1.2.2 Viewpoint from the chemical perspective

From a chemical perspective it was reported (Walsh and Kurz, 1979) that a SF_6/oil combination was chemically stable in the presence of cellular insulation and conventional conductor materials up to temperatures as high as 150°C.
In spite of conclusions regarding the electrically beneficial

or chemically deleterious effects of SF_6 being inconclusive, it was postulated (Denat et al, 1982) that corrosive products will be formed via reduction of the dissolved SF_6 at the cathode or after arcing in the SF_6/oil combination.

Chapter 2 : Gassing tests

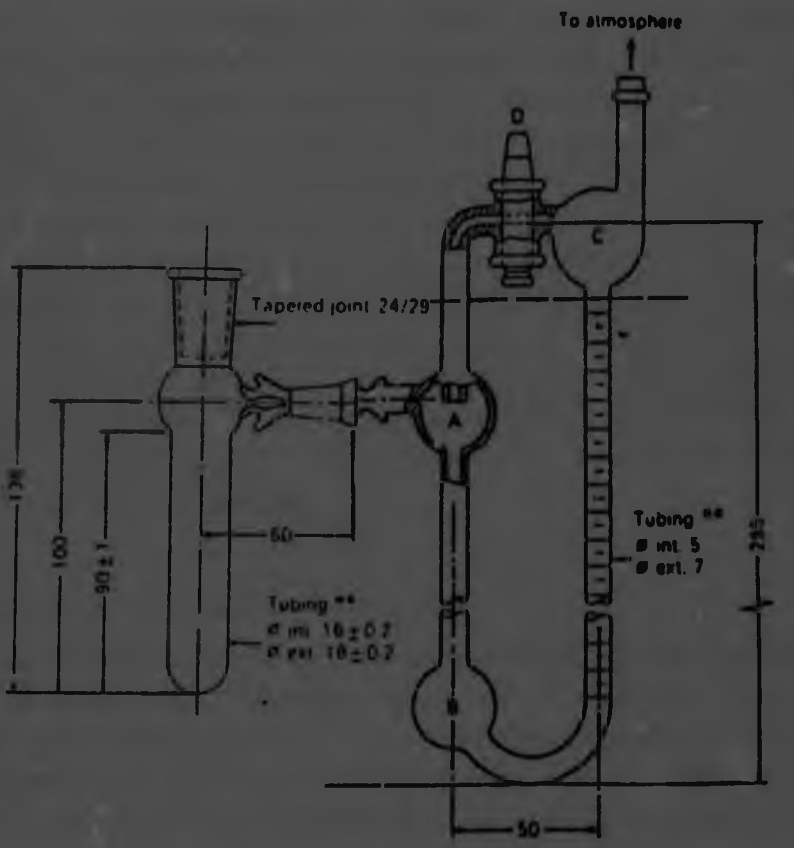
The gassing behaviour of any one insulation liquid is primarily a function of its chemistry, but changes in test parameters can modify the results significantly. An apparatus was put together to detect and compare these variations under a variety of temperature conditions. The experiments were performed to determine the gassing tendencies of various insulating liquids exposed to air and SF_6. Another of the objectives of these experiments was to ascertain the amount of SF_6 that can be contained by the insulating liquids (transformer oil and silicone liquid) under investigation. It should be noted that the gassing of a liquid refers to the gas evolution or gas absorption of that liquid.

2.1 Description of apparatus

The apparatus used is based on the Pirelli test apparatus presented in the British standards methods for testing the gas evolution or absorption of insulation liquids under various conditions (BS 5735).

2.1.1 The gassing-cell and gas burette assembly

A schematic diagram of the gassing-cell and gas burette assembly, made from borosilicate (Pyrex) glass, is presented in figure 2.1 . A description of this apparatus is presented in appendix A.



Dimensions in millimetres

A, B C = Glass bulbs

D = By-pass stopcock

Figure 2.1 - Gas Burette & Gassing-cell assembly
(Ref - BS 5795)

2.2 Experimental Method

Samples of air or SF_6 saturated transformer oil and samples of air or SF_6 saturated silicone liquid were tested in the gassing-cell and the gassing (ie. gas absorption or evolution) properties of the liquid being tested were measured over temperatures ranging from room temperature to $120°C$. A limit of $120°C$ was decided upon since the range $30°C$ - $120°C$ provided the results of the greatest value. In addition to this it was not desirable to heat the oil-bath to much higher levels and approach the flashpoint temperature of transformer oil, ($150°C$ - $200°C$) too closely. The detection of the gassing in a given sample was done on a continuous basis with readings taken at 30°, 60°, 90° and $120°C$. The experimental method is discussed in greater detail in appendix B

2.3 Calculation of gassing in samples

For the calculation of the gas evolved or absorbed by the samples it is necessary to consider the law of partial pressures $P_1 \cdot V_1/T_1 = constant = P_2 \cdot V_2/T_2$. For these measurements the pressure P is assumed to be constant giving $V = constant \cdot T$. The volume is assumed to be directly proportional to the temperature for the region under consideration. The volume of gas produced or absorbed by the liquid sample is read off in burette markings and converted to mm^3. For a specific temperature the volume of gas produced is simply calculated by $\Pi \cdot (2.5)^2 \cdot (B_{fin} - B_{init})$ where B_{init} is the initial level of the marker liquid in the gas burette and B_{fin} the burette level at the time of the reading.

2.4 Gassing test results

The following tests were carried out:

1] Gassing tests conducted at 60°C.

Comparison of SF_6 saturated transformer oil and silicone liquid and samples of the same liquids exposed to atmosphere for several days. These tests were all conducted at the steady temperature of 60°C. This is a temperature commonly reached by insulation in a transformer.

2] Temperature related gassing of three liquids.

Tests were carried out comparing the gassing, at various temperatures, of transformer oil and silicone liquid with a volatile insulating liquid. Comparison with a highly volatile liquid was done to place some perspective on the gas evolution of the two other liquids. A perchlorethelyne/Midol combination, which was readily available at the time, was used.

3] Gassing of air saturated transformer oil and silicone liquid.

A series of tests were then done comparing the gas evolution or absorption of transformer oil and silicone liquid which had been exposed to atmosphere under identical conditions.

4) Comparison of air and SF_6 saturated transformer oil and silicone liquid.

Samples of transformer oil exposed to atmosphere were compared to SF_6 saturated transformer oil at various temperatures to find out when SF_6 is evolved and how much SF_6 can be absorbed by transformer oil. Similar tests were undertaken using silicone liquid.

5) Heating and cooling tests.

Samples of transformer oil and silicone liquid were heated and then cooled to have a look at the gas evolution and re-absorption trends.

6) Gassing tests with paper present in liquid samples.

Insulating liquids were tested in the presence of paper insulation over a range of temperatures to determine to what extent the presence of paper will influence the gas evolved from the samples.

2.4.1 Gassing tests conducted at 60°C

Tests were conducted comparing SF_6 saturated transformer oil and silicone liquid as well as transformer oil which had been exposed to atmosphere for several weeks, thus ensuring it was air saturated and silicone liquid at a constant temperature of 60°C. Saturation of the samples with SF_6 took place overnight

under pressure ensuring complete saturation of these samples. The stopcock on the gas burette was not opened, unless it was necessary to prevent overflow, so the column pressure exerted by the marker liquid in the gas burette had some effect on the readings. The gassing measurements included the heating of the samples from 30°C - 60°C and the maintenance of these samples at this temperature for 5 hours. This heating from 30°C - 60°C took place in the first half hour.
8 ml liquid samples were used for testing.

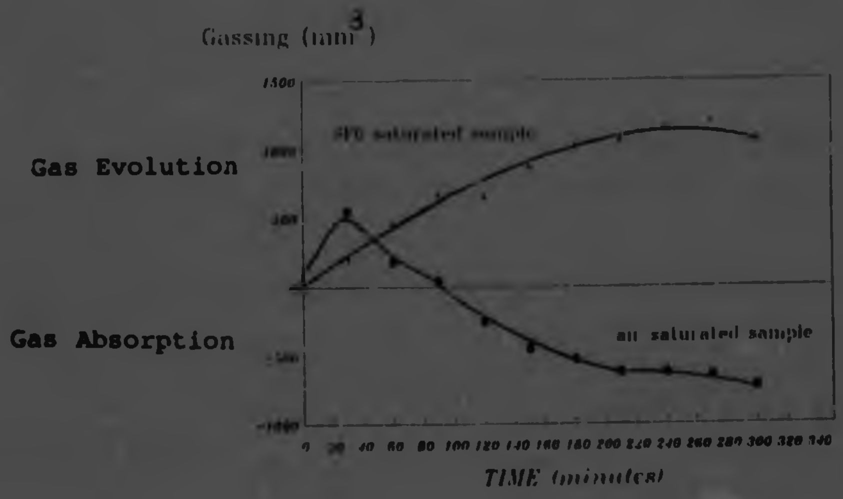


Figure - 2.2 Gassing of transformer oil
Comparison of Air and SF_6

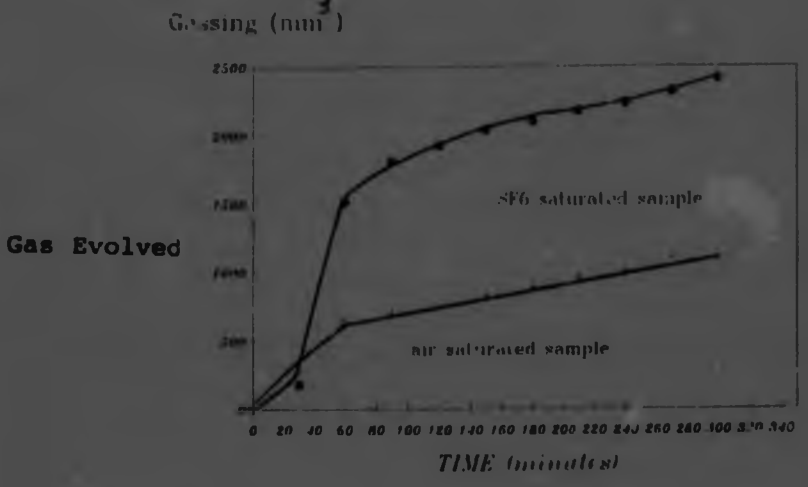


Figure - 2.3 Gassing of silicone liquid
Comparison of Air and SF_6

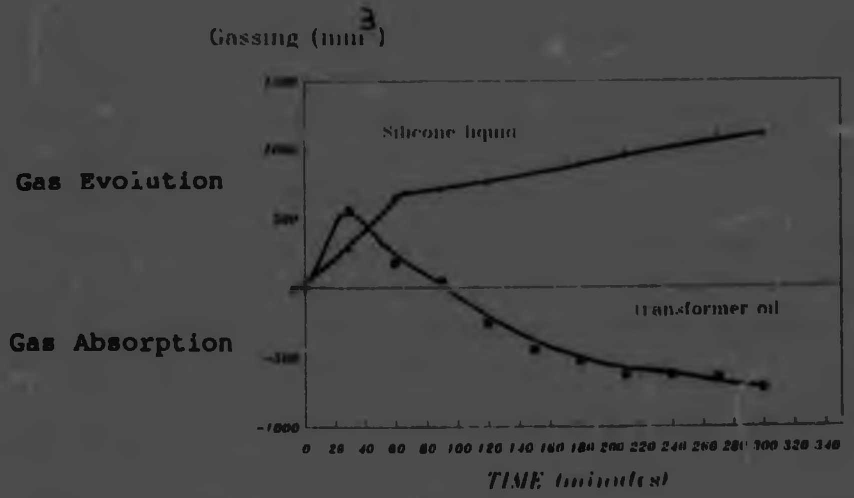


Figure - 2.4 Gassing of air saturated liquids
Comparison of transformer oil and silicone liquid

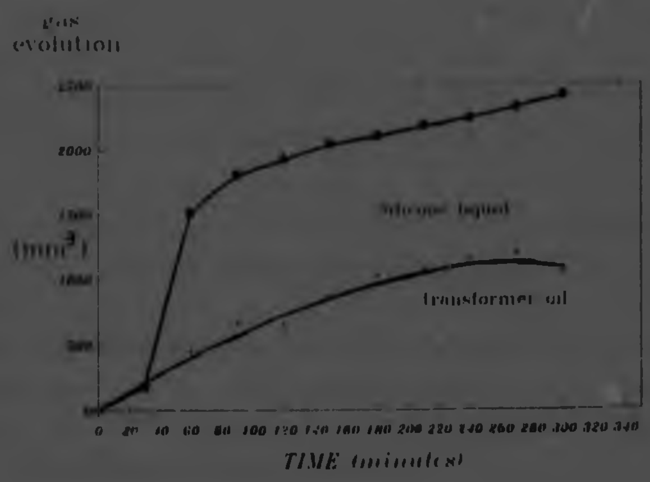


Figure 2.5 - gassing of SF_6 saturated liquids
Comparison of transformer oil and silicone liquid

The results of the test with new unsaturated transformer oil showed that after giving off gas for the first half hour the oil started to absorb gas. This process continued for the next 3 hours with the rate of absorption slowly levelling off. The reasons for this absorption are:

- The liquid was not saturated and the increase in temperature allowed it to absorb air, since the solubility of transformer oil increases with temperature (Brown Boveri, publication No DTR - 32 117E, 1981).
- The column pressure above the oil caused gas to be absorbed by the oil.

The SF_6 saturated transformer oil showed gas evolution for most of the time of the test with the bulk (75%) of this evolution taking place in the first half of the five hour experiment. The rate of gas evolution slowed down in the second half of the test and finally some re-absorption took place in the last half hour. Again this was very probably due to the column pressure which had built up thus forcing some re-absorption

No absorption took place in the test with air saturated silicone liquid but equilibrium was reached towards the end of the test (last hour).
An interesting observation is that the volume of gas evolved by the silicone liquid was almost identical to the volume of gas evolved by SF_6 saturated transformer oil under almost identical experimental conditions.

As far as the test with SF_6 saturated silicone liquid was concerned there was a large amount of gas evolution with 75% of this taking place in the first hour and a half after which the gassing rate remained steady until the end of the test. SF_6 Saturated silicone liquid had 56% more gas evolved by the end of the five hours than had the transformer oil under the same conditions. This test indicates that silicone liquid might have a higher gas content which it releases as the temperature increases from 30°C - 60°C.

2.4.2 Temperature related gassing of 3 insulating liquids

For this set of tests 10 ml samples of each liquid were tested with the stopcock of the gas burette being opened every half hour so pressure above the samples did not build up and affect the results. The atmospheric humidity was 30% for the transformer oil and silicone liquid and 53% for the perchlorethylene/Midol mixture. The expansion of the air in the gassing cell above the liquid samples for these tests was estimated to be 2500 mm^3.

The gassing properties of transformer oil, silicone liquid and a perchlorethylene/Midol mixture, all of which had been exposed to the same atmospheric conditions for quite a long time were tested and the results shown in table 2.2, Appendix C were achieved. The perchlorethylene/Midol solution showed a great deal of gassing. This was due to the evaporation of perchlorethylene which begins at 90°C.

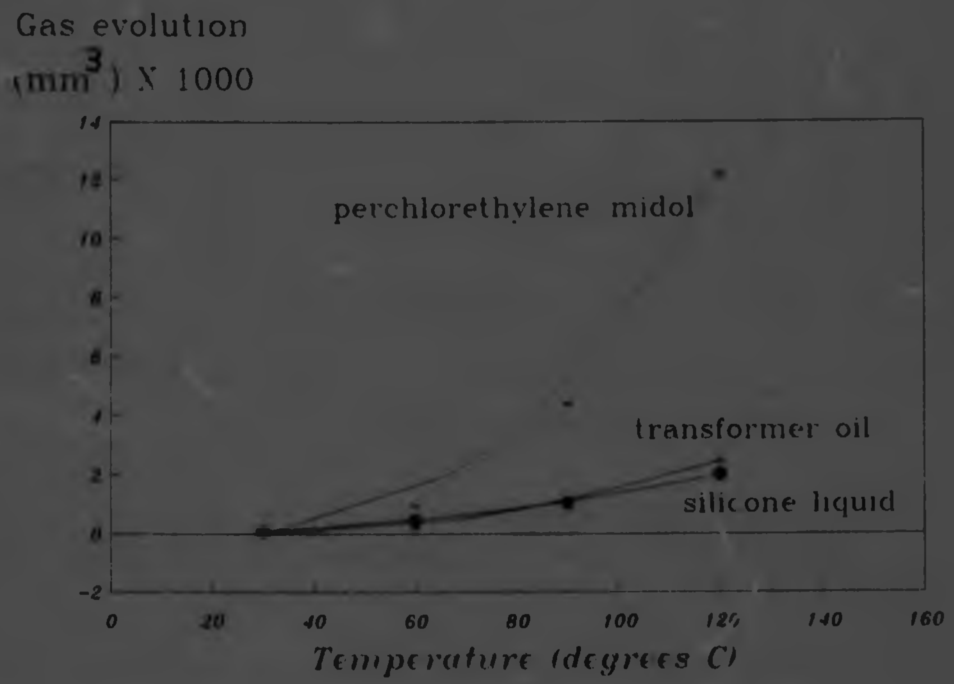


Figure 2.6 - Gassing of insulation liquids

2.4.3 Gassing of air saturated transformer oil and silicone liquid

The stopcock on the gas burette was kept closed for the period of gassing at a specific temperature. 8 ml Samples of transformer oil and silicone liquid were tested. The air humidity was $30\% - 35\%$ and the room temperature varied between $21°C - 23°C$ for tests with these two liquids. The expansion of the air in the gassing-cell was estimated to be $\approx 1865\ mm^3$ for every $30°C$ increase in the oil bath temperature.

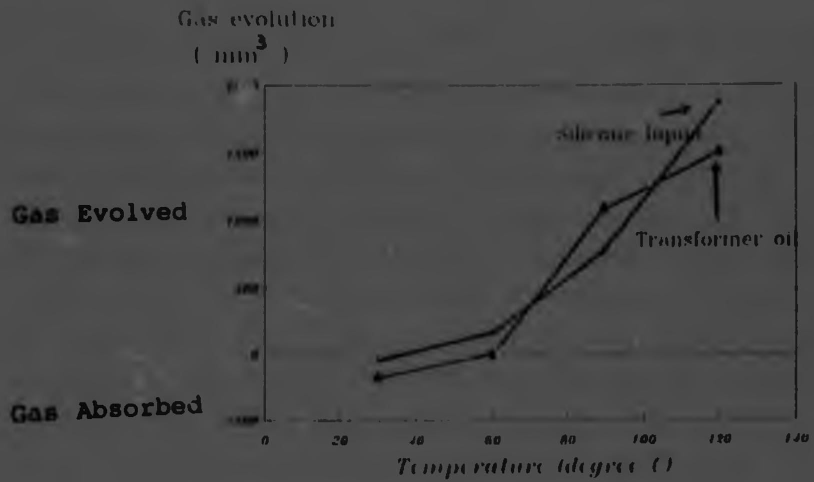


Figure 2.7 - Air saturated liquids
Comparison of transformer oil and silicone liquid

The transformer oil evolved a lesser amount of gas over the period of the experiment compared to the silicone liquid, which evolved 60% more gas. The silicone liquid's gas evolution increased steadily with temperature but the transformer oil

gave off more gas at lower temperatures, up to 90°C, and later reabsorbed some gas.
It was seen that for all tests the gas evolution of transformer oil peaked at 90°C and then levelled off or dropped, while the gas evolution of silicone liquid increased all the way to the temperature of 120°C. A factor that must be taken into account is; at the altitude (2000 m above sea level) at which these tests took place the boiling point of water is ≈90°C. As a result of this some of the gas evolved at this temperature must have been moisture evaporating.

2.4.4 Comparison of air and SF_6 saturated transformer oil

The gassing of air saturated transformer oil was compared to the gassing of SF_6 saturated transformer oil and these results are presented in table 2.4 in appendix C. SF_6 gas was bubbled through the relevant sample of transformer oil, overnight and a hour beforehand for this test. The room temperature for these tests was 21°C-22°C and the atmospheric humidity ranged between 34%-38%. The stopcock on the gas burette was not opened unless it was between heating up the samples.

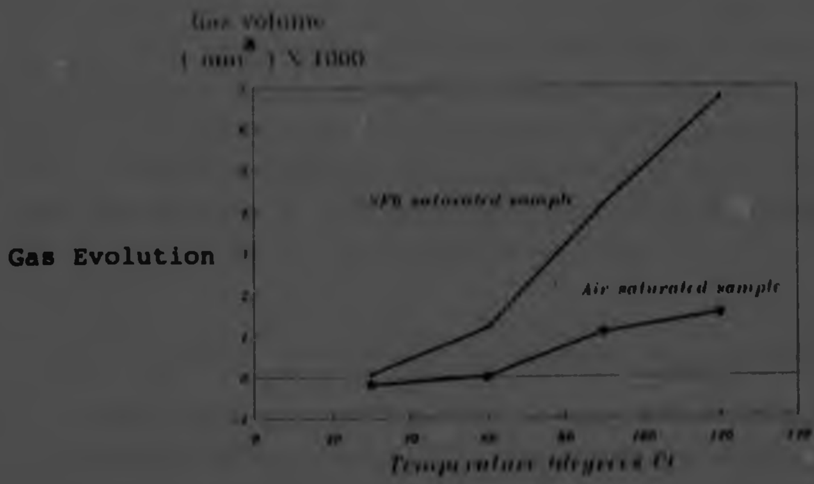


Figure 2.8 - Transformer oil
SF_6 & air saturated samples

The trends for the air and SF_6 saturated cases are the same with the volumes of gas evolved differing, as seen in figures 2.8 and 2.9. There was a slight tendency for transformer oil to reabsorb gas at 120°C. This phenomena did not seem to be related to temperature to any great extent but rather to a change in the partial pressure in the liquid. There was a definite oscillatory effect regarding the evolution and absorption of gas in a sample of transformer oil, which was not evident in silicone liquid. This effect was noticed more in tests without SF_6 in the oil. The results indicated in figure 2.8 indicate that, for the air saturated sample the gas evolution rate peaked at 90°C and it would seem to make little difference what the temperature is above this level. The reason for the gas evolution peaking at 90°C has been linked to the fact that this is very close to the boiling point of water at

2000 meters above sea level. As a result of this any water in the oil will form gas which will contribute to the volume of gas evolved at this temperature. However, this does not explain the much larger volume of gas evolved by SF_6 saturated samples with the same trends as the air saturated case, thus showing that the peaking of the gas evolution at this temperature is not related only to this moisture effect.

2.4.5 Comparison of air and SF_6 saturated silicone liquid

8 *ml* samples of silicone liquid, either air or SF_6 saturated, were tested under conditions of about 30% atmospheric humidity and the air expansion above the samples was estimated to be $\approx 1865\ mm^3$.

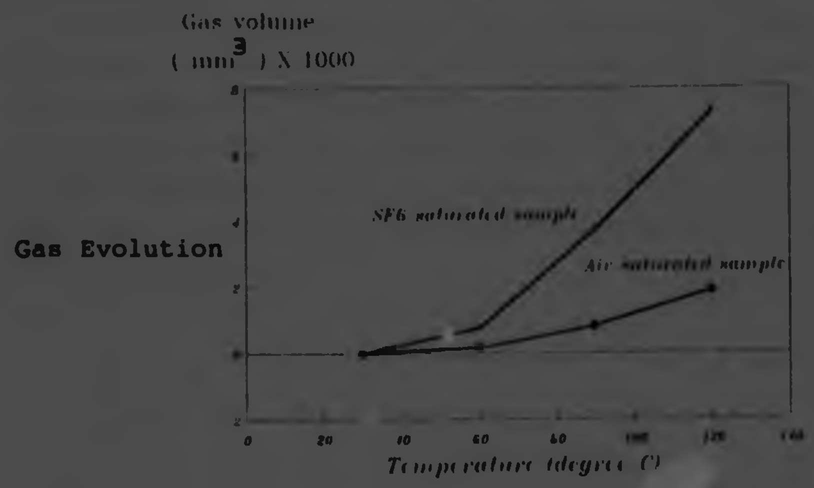


Figure 2.9 - Silicone liquid
Air saturated & SF_6 saturated samples

As can be seen in figure 2.9 SF_6 saturated silicone liquid gives off more gas than ordinary air saturated silicone liquid at all temperatures above 60°C . The trends are similar, with the gassing rate increasing steadily with temperature. After the samples had been observed for a gassing at 120°C for a lengthy period an estimate of the amount of SF_6 absorbed by the SF_6 saturated sample could be made by comparing it with the sample which had not been saturated with SF_6. The SF_6 saturated silicone liquid sample absorbed at least $\approx 5400\ mm^3$ of SF_6. This demonstrated that SF_6 is much more soluble in silicone liquid than air as the liquid managed to absorb a large amount of SF_6 after it was air saturated.

2.4.6 Heating and cooling tests

These tests compared 10 ml samples of silicone liquid and 10 ml samples of air saturated and unsaturated transformer oil which are first heated up to 120°C and then cooled to 30°C. The air expansion is estimated to be 2500 mm^3. The stop-cock on the gas burette, was opened only for an evaluation of the liquid expansion, before a change in the temperature of the sample was undortaken. A fan was used to speed up the cooling down of the oil bath.

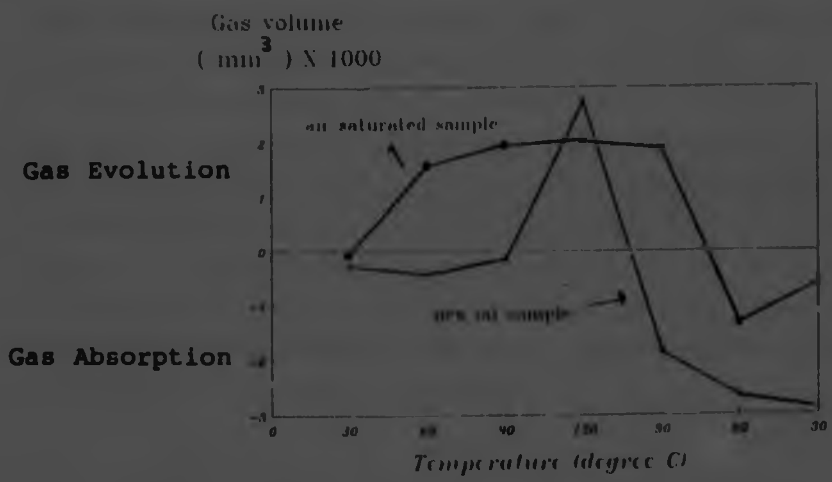


Figure 2.10 - Heating/cooling results
Unsaturated & air saturated transformer oil

The gassing of the transformer oil shows an oscillatory tendency, especially during cooling (ie. first the sample will over absorb gas and then emit some of this gas). As expected the partially gassed sample had absorbed gas by the end of the test. The high atmospheric humidity (60%) on the day of the test may have had some influence on this. In addition the higher solubility of transformer oil at high temperatures will allow the oil to have a higher gas content. The saturated transformer oil, not surprisingly, reabsorbed an amount of gas closer to that which it had evolved than the previous case. It was quite interesting to note that during cooling between 120 and 90 degrees there was little re-absorption, as can be seen in figure 2.10. This seems to concur with earlier observations that there is little difference over this temperature range as far as the gassing behaviour of air saturated transformer oil is concerned. Apart from these observations the results of heating and then cooling the samples did not offer any conclusive new insights.

The silicone liquid ended up having absorbed more gas than it gave off. The time factor might have something to do with this. If the experiment had continued for longer further re-absorption might have taken place. High humidity on the day of the test might have influenced this phenomenon. The fact that solubility of silicone liquid decreases with temperature might have some influence on the result obtained.

2.4.7 Gassing tests with paper in liquid samples

10 cm long strips of paper were submersed in 8 ml samples of whichever insulation liquid was being tested. The air expansion was estimated to be $1865\ mm^3$ and the humidity was $\approx 30\%$ for the samples. The room temperature during these tests was fairly constant at $\approx 22°C$.

It was expected that the paper would dominate the gas evolution in the samples tested. The gassing of the samples with paper present at $60°C$ was slightly more than the $60°C$ results of samples without paper present. At the higher temperatures the gassing of the samples with paper present was much higher than those without it. These relationships are shown in figures 2.11 - 2.14. This trend shows that the gas evolved by the paper increases with temperature. At $90°C$ - $120°C$ the paper begins degrading thus more gas was given off at these higher temperatures.

The trends with the samples having the paper present were similar to the trends that were noticed in samples without paper. Transformer oil gave off less gas than corresponding samples of silicone oil confirming again that silicone liquid has a higher overall gas solubility than transformer oil. The SF_6 saturated samples did not show as dramatic a difference in gassing between the samples where paper was present or not. This is due to the fact that the SF_6 saturated samples had a higher proportion of gas present in the liquids and the paper related gassing did not constitute as great a percentage of the gas evolved.

It was noticed that there was a far lesser difference in percentage gas evolved between the SF_6 gassed samples and the air s[illegible]ed samples compared to the cases where there was no pap[illegible]esent. This indicates that when paper is present the paper gassing dominates that of SF_6 or air in the liquid.

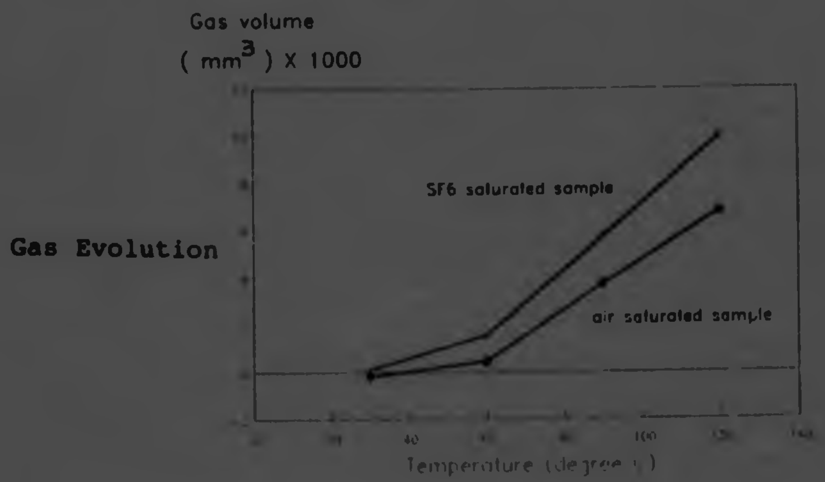


Figure 2.11 - Gassing of Transformer Oil and Paper (Air saturated & SF_6 saturated)

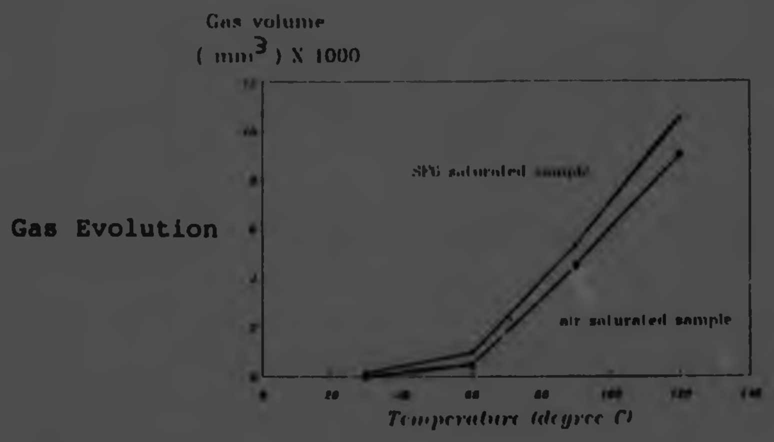


Figure 2.12 - Gassing of Silicone Liquid and Paper
(Air saturated & SF_6 saturated)

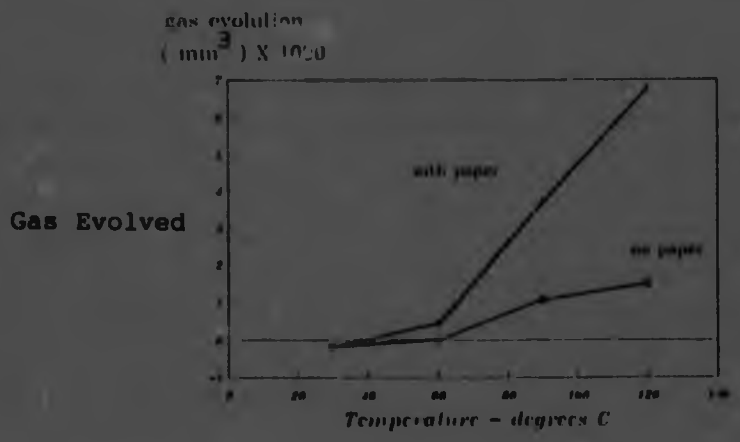


Figure 2.13 - Air Saturated Transformer Oil
(with and without paper insulation)

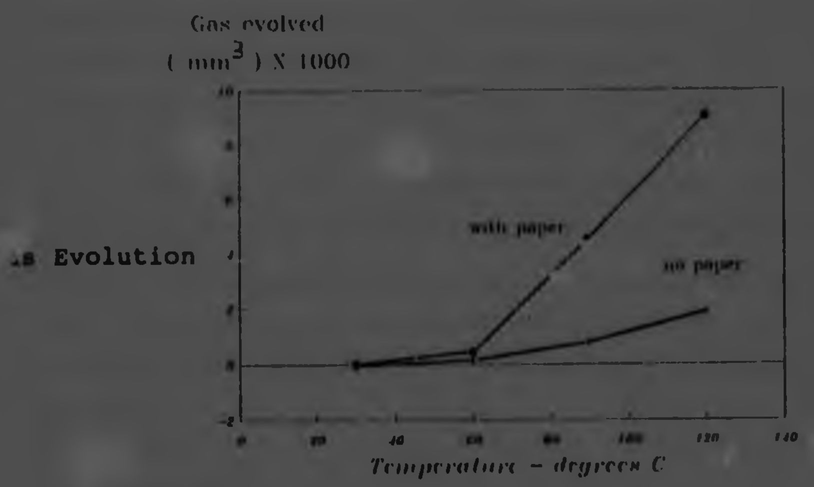


Figure 2.14 - Air Saturated silicone liquid (with and without paper)

The results so far have shown that for ordinary air saturated samples of transformer oil and silicone liquid there is over 4.5 times as much gas evolved at 120°C when paper is present. For SF_6 saturated samples there is 1.5 times as much gassing when paper is present (for both transformer oil and silicone liquid). The increase in gassing when paper is added to a sample is greater than the increase in gassing when the samples are saturated with SF_6. {(3.9 - 4.5) compared to (4.5 - 4.8) times as much gas evolved.}

2.5 Conclusions on gassing tests

The following conclusions have been drawn from the gassing experiments:

- The gas evolution of the gas saturated insulating liquids investigated increases with temperature for air and SF_6.
- In comparing silicone liquid with transformer oil, it was found that gas saturated silicone insulating liquid tends to evolve more gas than saturated mineral oil. This indicates that silicone liquid can absorb more gas than mineral oil.
- It was found that SF_6 saturated liquids evolve more gas with the progression of temperature than just air saturated liquids. This concurred with the earlier work (Brown Boveri, publication No DTR 81-117E, 1981) which stated that the solubility of SF_6 in the transformer oil is much greater than that of air in the same liquid.
- Transformer oil tends to reach its maximum gas evolution at $90°C$. After $90°C$ has been reached further temperature rises do not have a large effect on the gas evolution. For silicone liquid this maximum is reached at $120°C$.
- When the gas evolution of air and SF_6 saturated samples was investigated in the presence of paper insulation the paper, which provides a continuous source of CO, CO_2 and H_2O, dominated the gassing. It can be seen from this that it is not that important whether the liquid insulation is air or SF_6 saturated when one is concerned with the volume of the gas produced in the presence of paper insulation. The tests showed that the quantities of gas evolved in the presence of paper became substantially higher at and beyond the temperature of $60°C$. This is a cause for concern since $60°C$ is not an abnormal operating temperature in transformers.
- It was observed that transformer oil was much more sensitive to changes in partial pressure than was silicone liquid as was shown by the way gas was evolved and then reabsorbed in an oscillatory manner. This was observed in instances where

the column pressure above the transformer oil caused some reabsorption, even at high temperatures. This situation did not remain consistent but oscillated as the liquid later gave off gas again. The same phenomena was noticed during the cooling of the samples. This phenomena did not occur in silicone liquid.

Chapter 3 : Partial discharge activity of liquids sealed in air tight gap

The group of experiments described in this chapter were conducted to ascertain the ability of liquid insulation which has been saturated with SF_6 to quench partial discharges impinging on them. The experiments were performed using enclosed samples of silicone liquid and transformer oil which had been SF_6 saturated, or just air saturated for comparison. In addition to this it was desired to observe if the products of the partial discharges attacked either of the brass electrodes used or the paper insulation exposed to these by-products. Another objective of these experiments was to find out if the behaviour of the various samples could be linked to the results of the gassing tests described in the previous section.

3.1 Apparatus

The apparatus used for the tests reported here is shown in figure 3.1. For these tests the gap, with a diameter of 20 mm, was filled with the liquid to be tested leaving an air pocket approximately 0.5 mm deep. The gap was sealed with O-rings. A plane to plane electrode formation was used. The cylindrical cavity was drilled in a 10 mm thick sheet of perspex, with another perspex sheet present above this and the ground electrode beneath it. The high voltage electrode was placed above the top, unmarred, perspex covering. These sheets of perspex and the flat circular electrodes were held together by plastic nuts and bolts which along with additional perspex plates held the partial discharge cell together and ensured that the liquid and gas samples were air-tight. This apparatus was completely submerged in a oil bath and stressed. The placement of the discharge cell in the oil-bath ensured that there would be no other partial discharge sources encountered. The discharges were detected using an ERA partial discharge detector.

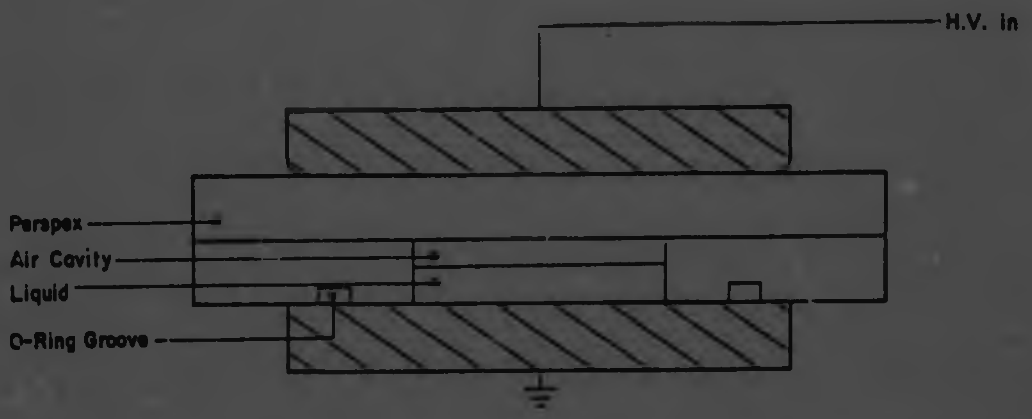


Figure 3.1 - Partial discharge cell

3.2 Experimental procedure

The samples were saturated with SF_6 or left exposed to air before being placed in the gap. The samples were then sealed in the apparatus leaving an air gap. Increasing AC voltages were applied until the partial discharge inception voltage was detected. The voltage was then raised by 5 kV above the inception voltage (~30% above inception voltage) and the partial discharge activity was measured. A partial discharge inception level of 50 - 100 pC was used for this set of investigations. The partial discharge inception and extinction voltages were noted but these values were not regarded as being significant as the air gap above the liquid sample could not be accurately gauged. The initial discharge magnitude was noted as was the change in discharge magnitude with time. The total stressing period for the test cell was usually thirty minutes. In some cases the partial discharge cell was stressed for quite a long time to investigate the effects of any partial discharge by-products as well as to investigate the long term behaviour of these discharges.

After each test was completed the partial discharge cell was thoroughly cleaned using an industrial cleaning solvent. The SF_6 saturated samples were saturated using the Pirelli apparatus described previously, where the stopcock was maintained in a closed position thus ensuring that some pressure would be exerted above these samples. This gas saturation was performed for at least an hour before the test.

3.3 Paper degradation tests

An SF_6 saturated sample of transformer oil was placed in the gap with strips of paper insulation between the air gap and the perspex and between the ground electrode and the liquid sample. The same thing was done with SF_6 saturated silicone liquid. These samples were stressed at 5 kV above inception voltage for a long period of time (48 hours - 3 days).

3.4 Experimental results

The results of the 30 minute experiments are presented in table 3.1 and their relationship is expressed in figures 3.2 and 3.3. The partial discharge magnitudes are represented in percentage variations from the initial value. This magnitude was approximately 200 pC for these tests

Table 3.1 - Change in partial discharge magnitudes with respect to time as a % of the discharge magnitude

Time (minutes)	New mineral oil	Air saturated mineral oil	SF_6 saturated mineral oil	Air saturated silicone liquid	SF_6 saturated silicone liquid
0	100	100	100	100	100
5	63	89	141	71	45
10	282	112	50	63	45
15	282	141	50	56	56
20	251	141	45	40	25
25	224	141	40	100	28
30	224	159	45	80	20

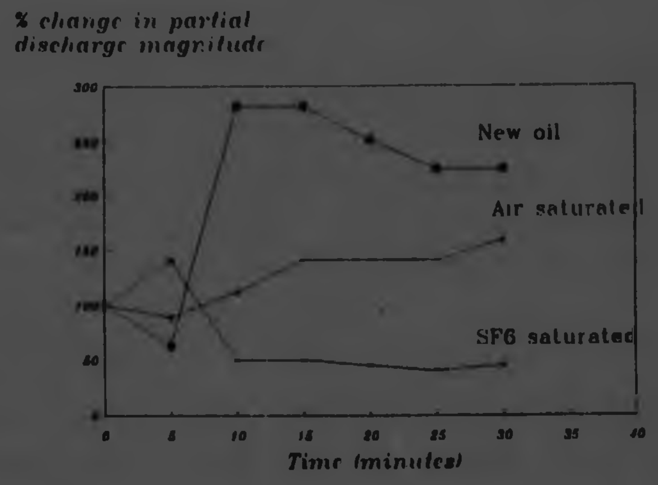


Figure 3.2 - Partial discharge magnitude - Transformer oil

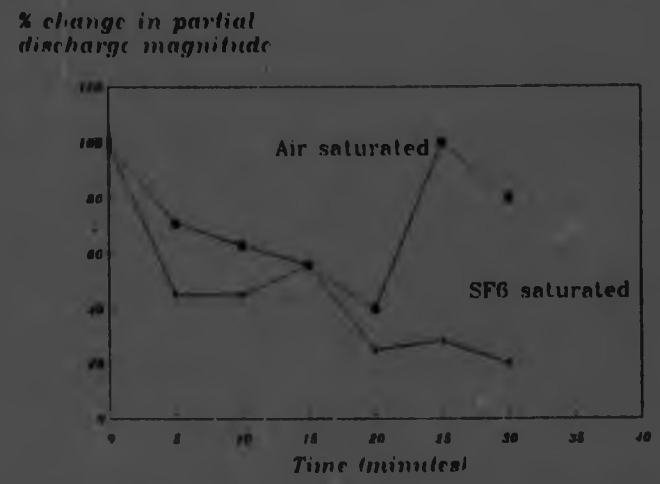


Figure 3.3 - Partial discharge magnitude - Silicone liquid

3.4.1 New transformer oil

The new transformer oil which had not been exposed to the atmosphere for any length of time (less than 8 hours) was introduced into the test cell and the test showed a large increase in partial discharge magnitude 10 minutes into the test. The situation remained fairly constant for the remainder of the test. Upon being unsealed the sample exhibited a partial vacuum effect above the liquid.

3.4.2 Transformer oil exposed to air for a lengthy period

In most tests with these type of samples there was little change in the partial discharge activity over the thirty minute stressing period. The greatest change in the results for this test is indicated in table 3.1, where a slight increase in discharge magnitude was noted.

3.4.3 SF_6 saturated transformer oil

The SF_6 saturated sample of mineral oil exhibited a large decrease in the discharge magnitude after 10 minutes. The partial discharge magnitude remained constant for the remainder of the stressing period whilst the number of discharges per unit time decreased. It appeared that "quiet" periods, of the order of a few cycles, occurred during which time there was no discharge activity.

3.4.4 Silicone liquid exposed to air for a lengthy period

When silicone liquid (air saturated) was introduced into the test cell, a decrease in the discharge magnitude occurred with the number of discharges per unit time also decreasing. Large discharges of the same magnitude as the initial discharges appeared intermittently. At one stage of the test these discharges disappeared altogether (15-20 minutes into the test) but they later reappeared.

3.4.5 SF_6 saturated silicone liquid

With SF_6 saturated silicone liquid in the cavity there was an immediate decrease in the partial discharge magnitudes and the number of discharges per unit time. This trend continued for 15 minutes until very few discharges, which were of reduced magnitude, remained. After twenty minutes the discharges were of greatly diminished magnitude (20% of the original magnitude). They did not reappear at any further time in the test.

3.4.6 Paper degradation tests

The sample with paper and SF_6 saturated transformer oil, which was stressed for just under 48 hours, showed a very slight increase in partial discharge magnitude at the latter stage of the test compared to the initial part of the test. A SF_6 saturated sample of silicone oil was used in a similar test except that test had a duration of three days. After five hours there was little change in the partial discharge magnitudes or the regularity with which they occurred. After three days there was possibly a slight decrease in the partial discharge magnitudes. The paper samples when inspected by the naked eye did not show any signs of damage. They also did not show signs of damage when observed under a microscope.

3.5 Discussion

3.5.1 New transformer oil

The following explanation to the behaviour of the discharges in the new transformer oil is proposed. The transformer oil was not well gas saturated and it is expected that this transformer oil would absorb the gas from the gap above it (as is indicated by the vacuum type effect noticed when the apparatus was unsealed after the test). The decrease in pressure accounts for the increases in the partial discharge magnitudes. The decrease in pressure indicates that these are fewer molecules available to impede avalanche amplification. There will be fewer opportunities for electrons to collide with large heavy atoms and thus the mean free path of the electrons will be increased.

When a sample of air saturated transformer oil was used a lot less happened as it is unlikely that a great deal absorption of gas would take place, so the results in this case indicated a significantly reduced change in the partial discharge activity compared to the previous case.

3.5.2 SF_6 saturated transformer oil

The decrease in the partial discharge magnitudes in this case occurred because of the presence of the SF_6. The electronegative influence of SF_6 in the gap above the sample was responsible for the removal of electrons available for producing avalanches, resulting in the decrease in the discharge magnitudes. This decrease did not take place immediately and it was about 7-10 minutes into the test before any significant decreases in the magnitudes of the discharges were observed. This delay occurred because it was necessary for sufficient SF_6 to evolve from the liquid so that a discharge extinguishing electronegative vapour could form, as the discharges caused a release of gas from the liquid. The oil samples which were SF_6 saturated and thus (from the results of the gassing tests) had a far greater gas content would evolve sufficient gas to have a pressure build-up above the liquid. This pressure above the sample would have some influence on the reduction of the partial discharge magnitude.

3.5.3 Air saturated silicone liquid

The decrease in the number of discharges per unit time and their magnitude could be related to pressure exerted by gas evolved from the liquid on the liquids' surface. This explains the fact that there were long intervals (≈ 5 minutes) when the discharge magnitudes were greatly reduced. Changes in partial pressures and gas being reabsorbed into the liquid once the discharges were greatly reduced could account for the fact that discharges of the original magnitude reappeared.

3.5.4 SF_6 saturated silicone liquid

Compared to the non SF_6 saturated sample, as in the case of the transformer oil. the partial discharge diminishing property is much superior. In addition the SF_6 saturated silicone liquid shows better discharge quenching properties than the corresponding SF_6 saturated transformer oil sample (50% better). This is due to the differing chemical compositions of the two liquids or the fact that the silicone liquid had more gas present compared to the transformer oil, as has been shown in the gassing tests.

3.5.5 Tests conducted over a longer period than 30 minutes

Tests were conducted over a longer period than the thirty minutes of the measurements accomplished previously. These longer tests did not, however, shed additional light on the results reached before. There was very little change in the partial discharge activity after the initial half hour.

3.6 Conclusions

The following points may be concluded from the experiments run using the partial discharge cell.

- The ability of the insulating liquids, which have been saturated with SF_6, to drastically reduce the magnitude of partial discharges impinging on them is a significant electrical benefit of the presence of SF_6 in these liquids.
- SF_6 saturated silicone liquid shows greater partial discharge magnitude reducing properties than does SF_6 saturated transformer oil.
- A point of interest is that the gassing properties of SF_6 or air saturated silicone liquid and transformer oil is related to the partial discharge extinguishing abilities of these specimens: The silicone liquid with its propensity to absorb larger amounts of gas, in comparison to transformer oil, did reduce the discharge activity by a greater amount. This is seen to be due to the availability of a higher number of SF_6 molecules for the absorption of electrons as well as a greater number of gas molecules available to come out of the liquid and reduce the mean free path of electrons.

- There was no evidence of any chemical disadvantages as a result of partial discharges in SF_6 saturated transformer oil or silicone liquid

Chapter 4 : Partial discharge activity in SF_6 and N_2 bubbles in transformer oil

The tests described in this chapter explore the partial discharge activity in SF_6 and N_2 bubbles in transformer oil. It was desired to compare the SF_6 and N_2 with respect to inception and extinction voltages. Another intention was to try to confirm the partial discharge quenching results described in the previous section.

4.1 Bubble mechanisms

It has been found (Kaufmann, 1977) that bubble behaviour is very sensitive to the pressure of the bubble contents, with either expansion or contraction occurring, depending on the internal pressure in the bubble. It is noted (Nelson and Hasad, 1981) that a bubble, which is spherical in shape, expands and contracts as the internal pressure of the bubble varies.

It has been established that bubbles formed in a dielectric liquid contract and expand with a large variation in bubble radius (Bakale and Shmidt. 1981). This is supported by findings (Kaufmann, 1977) which discusses the observation that bubbles will be elongated in an electric field to take up the shape of a prolate spheroid. A change in electric field across the bubble will result in a change of bubble radius.

Observations (Meyrueix, Petriat and Tobazoen, 1982) concerning the behaviour of bubbles subjected to an increasing voltage, discovered the following:

> The bubble will become elongated after a certain threshold voltage. Numerous narrow branches will be formed. At a certain

voltage, which is sufficiently high, spraying will occur with small bubbles being ejected from and then returning to the main bubble.

It is well known that under electric field conditions:

1] Small bubbles tend to collect together to form large entities.

2] Large bubbles tend to "bridge" the electrode gap. A possible reason for this is suggested to be a stored energy phenomenon. By assuming this elongated shape the bubbles exhibit a reduced capacitance and consequentially less stored energy.

4.2 Apparatus

A versatile apparatus, for the measurement of the partial discharge activity of insulating liquids under various gaseous atmospheres and pressures, was put together as shown in figure 4.1. The apparatus assembled allowed for the heating up of the liquid and the partial degassing of the liquid. It also allowed for the adjustment of the gap size between parallel and point electrodes. The apparatus set up provided reasonable scope for the depth of the electrodes in the liquid to be varied.

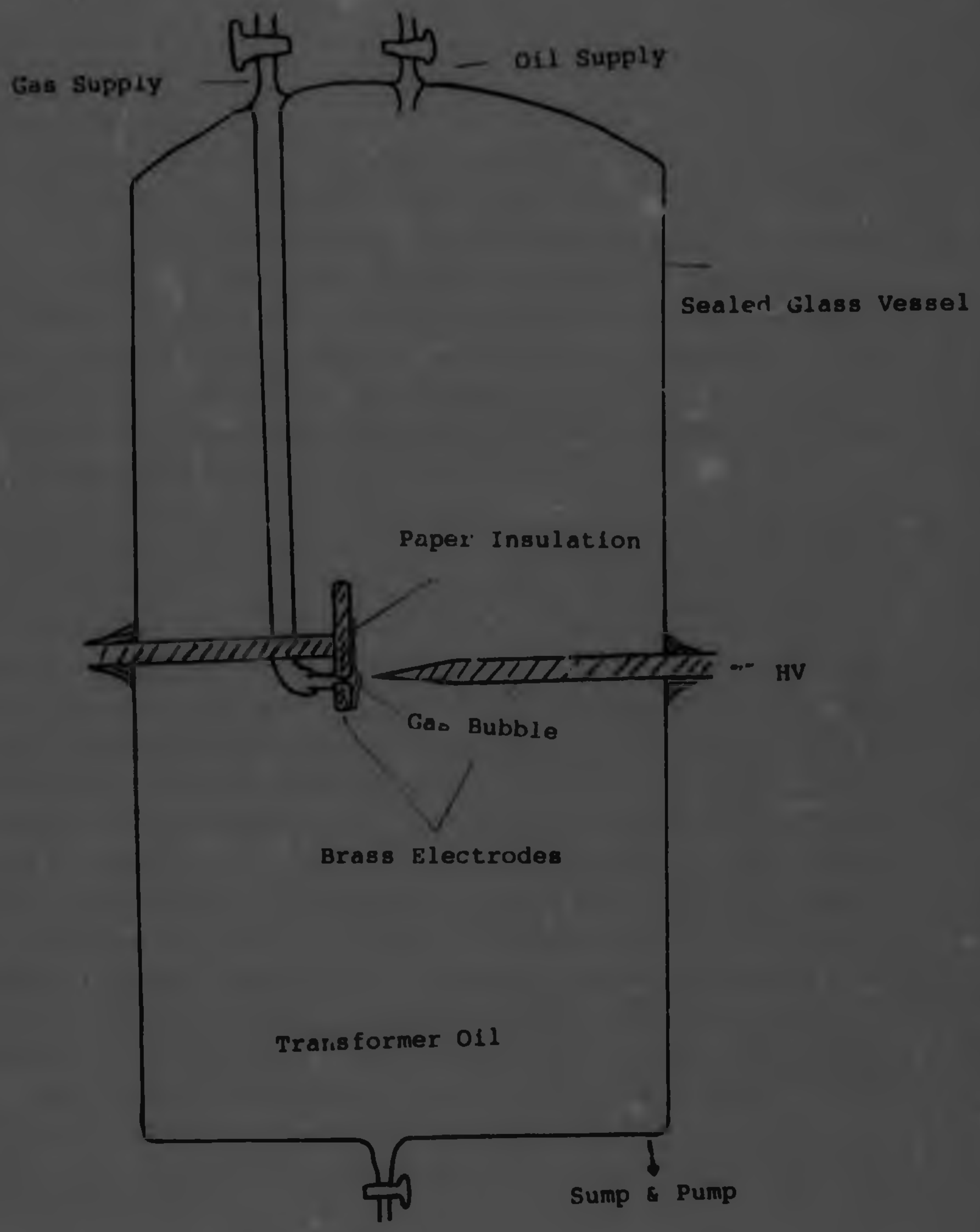


Figure 4.1 - Apparatus for Investigating Partial Discharge Activities

4.2.1 Glassware

Two vessels were made using thick Pyrex glass. The size constraints of the vessels took into account the electrode positioning, the fitting together of the vessels to other parts of the apparatus, the positioning of inlets and outlets and the amount of liquid the vessel could contain. The vessels, made circular for strength and convenience, consisted of two segments; the body of the vessel and the lid which fits onto it. The body of the vessel was made with two 10 mm wide openings (with extended tubes) opposite each other for the fitting of the electrode shafts. A 10 mm wide outlet under the vessel for the removal of the insulating liquid was present. The glass at the openings for the electrode shafts was thickened to give added strength for holding the shaft and electrode.

The lid which was removable for ease of work in the vessel had four inlets or outlets. The centre inlet, with a diameter of 8 mm , was to be used as the inlet for the insertion of the insulating liquid into the vessel. There were two other tubed openings, with diameters of 10 mm , one for the supply of SF_6 o other gas and the other for a vacuum inlet. Both these inlets were fitted with stopcocks. The last opening, ending in a tapered tube, was for the attachment of a pressure/vacuum gauge. The glass vessel and lid are depicted in figure 4.1 . In addition to this two gas collection bottles were made in case it was necessary to obtain gas samples given off during partial discharge activity. If such a collection was desired the whole vessel could be sealed and a connection to the gas collection bottle made. Gas could be collected with the aid of a vacuum pump.

4.2.2 Electrode arrangement

Circular brass electrodes with diameters of 5 cm and a thickness of 5 mm were made. Each electrode was fashioned with a protruding section, 7 mm long, behind it. Holes with diameters of 6 mm were bored into the centres of these protruding segments for the attachment of threaded shaft ends. The shafts were made 22 cm long and 6 mm in diameter to just have enough clearance to fit into the tubes on the sides of the glas test vessels. The electrode rods were threaded at the one end for the attachment of the electrodes and adjustments could be made to give varying gap sizes once the shafts were locked into place opposite each other in the side of the test vessel. The electrode and electrode rod arrangement is shown in figure 4.2.

The plane electrode surfaces facing each other were polished smooth with fine water-paper and then Brass polish and finally cleaned with industrial cleaning fluid before being used for testing. In some of the plate electrodes facing each other a strategically placed, 1 mm wide, hole through which gas bubbles were to emanate was drilled. In these cases short lengths of copper duct, for the attachment of tubing transporting the gas to be submitted to the stressed region between the electrodes, were brazed to the rear side of the electrodes.

Point electrodes were made by brazing a short length of copper wire to the end of the electrode shaft which was sharpened to a point. The result was a sharp pliable tip which could be moved into position directly opposite trapped bubbles being studied.

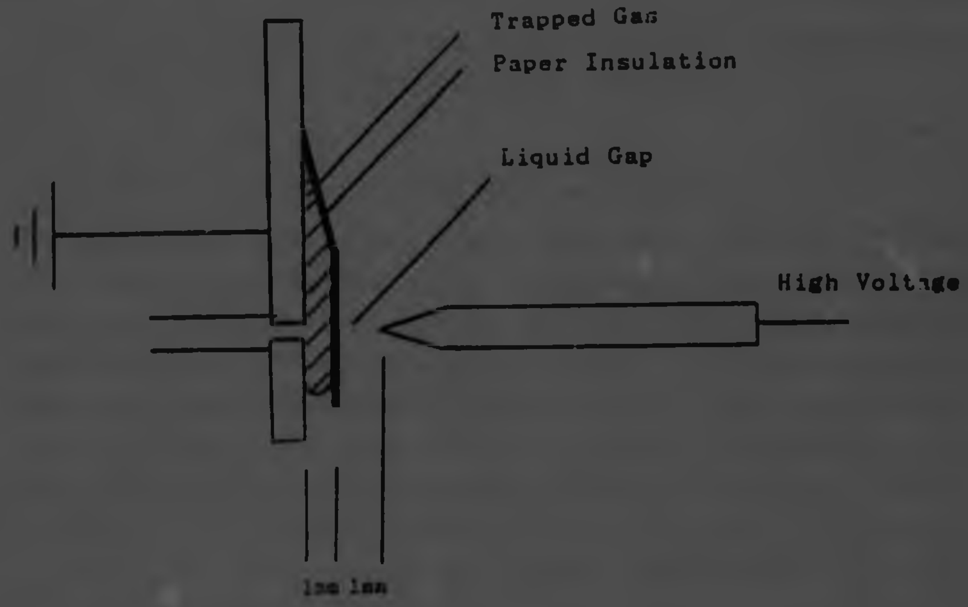


Figure 4.2 - Experimental Apparatus to determine Trapped Bubble Behaviour

4.2.3 Gas supply equipment

Two canisters of gas were used for these experiments. The one canister contained sulphurhexafluoride and the other contained nitrogen. The canisters were attached with a pressure release valve. This valve led to an inlet tube on the test vessel lid. Leaving this glass tube on the inner side was a plastic conduit for the further transport of gas to the back of the ground electrode. This tube was inserted and glued into the segment of copper tubing at the back of the electrode.

4.2.4 Electrical connections and attachments

The electrodes and their shafts were held in place by means of a plumbing arrangement and sealed with PTFE (Teflon) tape and putty. The plane electrodes through which the gas bubbles emanated were used as ground electrodes. The cable supplying the high tension was passed through a 1.5 m long flexible hose and attached to the high voltage electrode arrangement. This tube and the plumbing arrangement attaching the electrode shaft to the gas vessel was wrapped with a continuous narrow strip of tin foil. This in turn was wrapped with insulation tape. This screen minimised noise from the system so that when detection of partial discharges took place it could be confidently felt that the discharges noted were genuine partial discharges in the gas bubbles being examined. The other end of this connection was attached to the transformer arrangement.

Detection of the partial discharges was done using an ERA model 3 partial discharge detector.

4.3 Experimental method

The test vessels and other apparatus was cleaned thoroughly with industrial solvent before use.

Initially a plane to plane electrode arrangement was utilized and a tube of soft plastic with its outlet point situated directly beneath the electrode gap was used to introduce the gas.

A much better method for controlling the bubbling was utilized as has already been mentioned in the previous section. A small hole was made in the ground electrode through which gas was bubbled so that it would materialise between the electrodes. A problem that remained was that these bubbles still tended to bridge the gap between the flat electrodes by elongating when subjected to high voltages.

To overcome this problem paper insulation was fastened onto the ground plane electrode covering the region of the gas release hole in such a manner that a bubble would be trapped by the paper insulation situated against the ground electrode. This arrangement was suitable because it enabled gas bubbles to be either trapped or moved from behind the paper at various speeds. If the pressure from the gas canister was released it was possible for an ensnared bubble to return back up the tube from where it came. It was also possible that a trapped bubble may have become dislodged from its confined position. To counter these effects the canister valve was left slightly open so that in effect when a "trapped bubble" was being investigated a bubble was pushed out and replaced every 1/2 to 2 minutes. This was not seen to affect the concept of a "trapped bubble" to any great extent.

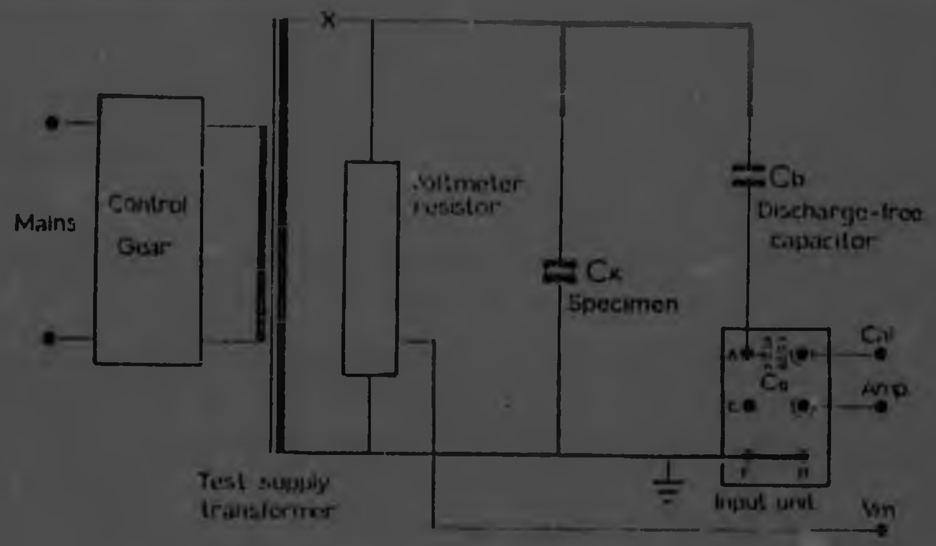
Better results were obtained when a point to plane electrode arrangement was used rather than a plane to plane arrangement. This was due to the fact that with the point/plane field it was possible to know the exact location of the most highly stresses region and the electric field could be centred onto the trapped bubble. It should be noted that the point electrode was the high voltage electrode. It should also be pointed out that the results with this arrangement were more repeatable and there was no long concern that the partial discharges monitored might be due to some cause other than that of the trapped bubble.

The two types of gas compared were SF_6 and N_2. When a change of the gas being used was made, the oil in the test vessel was replaced. The oil was also replaced with new oil after breakdown took place across the electrode gap. This "new" oil, however, was usually exposed to atmospheric conditions for about a day before the tests took place. In other cases the oil was pumped through the filter between tests. 2.75 *l* of transformer oil was used for each of these tests.

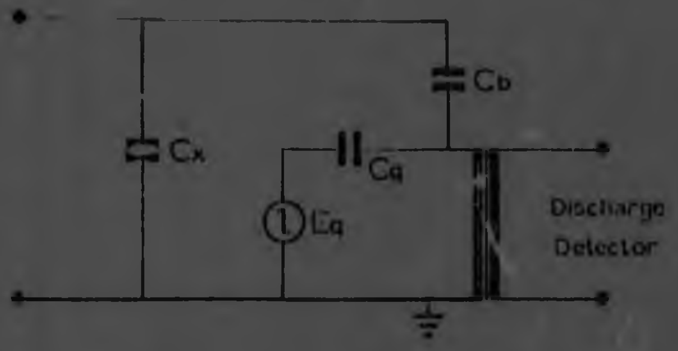
Detection of the partial discharges, using the ERA detector, was done at voltage increments of 1 kV. At each voltage observations were made to ascertain what, if any, activity was taking place at that particular voltage level. This was continued until the inception voltage was reached, at which point the situation was monitored. The initial observations were done at a very high gain to pick up any small discharges (in the 5 pC range) before the inception level was reached. It should be noted that the inception voltage was taken at the voltage where regular partial discharges > 500 *pC* were observed. This value was selected because it represented a clear transition between the nominal discharge levels detected at lower voltages and the much higher readings which confirmed partial discharge activity taking place across the trapped bubble, as can be seen in tables 4.2 and 4.3.

In selected cases liquid samples were collected after an experiment had been completed. For most tests a gap of 1 mm, measured using a feeler gauge, was used. This gap size was chosen in order to get results that would not stretch the limits of the high voltage generating equipment, while at the same time keeping the gap size large enough to ensure that there was a sufficient insulation liquid width to avoid breakdowns across the stressed region when discharges occurred in the trapped bubble. The liquid level in the glass vessel was maintained at a consistent level for all tests so that liquid pressure on the bubbles would not have any effect on the comparative results. The tests were conducted at room temperature. Before any testing was done with bubbles the system was tested and modified to eliminate any other corona sources. The system was set up so that there was no discernible background noise.

The measurement circuit is shown in figure 4.3. C_b is much larger than C_x and the discharge magnitudes pC were calculated using table 4.1 and figure 4.3 .



Standard test circuit



HF equivalent circuit

Test circuit load $C_x + C_b$

Discharge magnitude $Q_x = E_q C_q (1 + \frac{C_x}{C_b})$

For maximum sensitivity $C_b \gg C_x$

Figure 4.3 - Test Circuit and HF equivalent circuit

Table 4.1 - Step-Wave output for each Attenuator Setting

db	Voltage	db	Voltage	db	Voltage	db	Voltage
0	100 V	40	1.00 V	80	10.0 mV	120	100 µV
1	89.1 V	41	891 mV	81	8.91 mV	121	89.1 µV
2	79.4 V	42	794 mV	82	7.94 mV	122	79.4 µV
3	70.8 V	43	708 mV	83	7.08 mV	123	70.8 µV
4	63.1 V	44	631 mV	84	6.31 mV	124	63.1 µV
5	56.2 V	45	562 mV	85	5.62 mV	125	56.2 µV
6	50.1 V	46	501 mV	86	5.01 mV	126	50.1 µV
7	44.7 V	47	447 mV	87	4.47 mV	127	44.7 µV
8	39.8 V	48	398 mV	88	3.98 mV	128	39.8 µV
9	35.5 V	49	355 mV	89	3.55 mV	129	35.5 µV
10	31.6 V	50	316 mV	90	3.16 mV	130	31.6 µV
11	28.2 V	51	282 mV	91	2.82 mV	131	28.2 µV
12	25.1 V	52	251 mV	92	2.51 mV	132	25.1 µV
13	22.4 V	53	224 mV	93	2.24 mV	133	22.4 µV
14	20.0 V	54	200 mV	94	2.00 mV	134	20.0 µV
15	17.8 V	55	178 mV	95	1.78 mV	135	17.8 µV
16	15.9 V	56	159 mV	96	1.59 mV	136	15.9 µV
17	14.1 V	57	141 mV	97	1.41 mV	137	14.1 µV
18	12.6 V	58	126 mV	98	1.26 mV	138	12.6 µV
19	11.2 V	59	112 mV	99	1.12 mV	139	11.2 µV
20	10.0 V	60	100 mV	100	1.00 mV	140	10.0 µV
21	8.91 V	61	89.1 mV	101	891 µV		
22	7.94 V	62	79.4 mV	102	794 µV		
23	7.08 V	63	70.8 mV	103	708 µV		
24	6.31 V	64	63.1 mV	104	631 µV		
25	5.62 V	65	56.2 mV	105	562 µV		
26	5.01 V	66	50.1 mV	106	501 µV		
27	4.47 V	67	44.7 mV	107	447 µV		
28	3.98 V	68	39.8 mV	108	398 µV		
29	3.55 V	69	35.5 mV	109	355 µV		
30	3.16 V	70	31.6 mV	110	316 µV		
31	2.82 V	71	28.2 mV	111	282 µV		
32	2.51 V	72	25.1 mV	112	251 µV		
33	2.24 V	73	22.4 mV	113	224 µV		
34	2.00 V	74	20.0 mV	114	200 µV		
35	1.78 V	75	17.8 mV	115	178 µV		
36	1.59 V	76	15.9 mV	116	159 µV		
37	1.41 V	77	14.1 mV	117	141 µV		
38	1.26 V	78	12.6 mV	118	126 µV		
39	1.12 V	79	11.2 mV	119	112 µV		

4.4 Results

The results, presented in table 4.2, compare the partial discharge activity in trapped SF_6 and N_2 bubbles in transformer oil. The test voltage was raised and the partial discharges observed until breakdown occurred.

The following was seen from the results obtained.

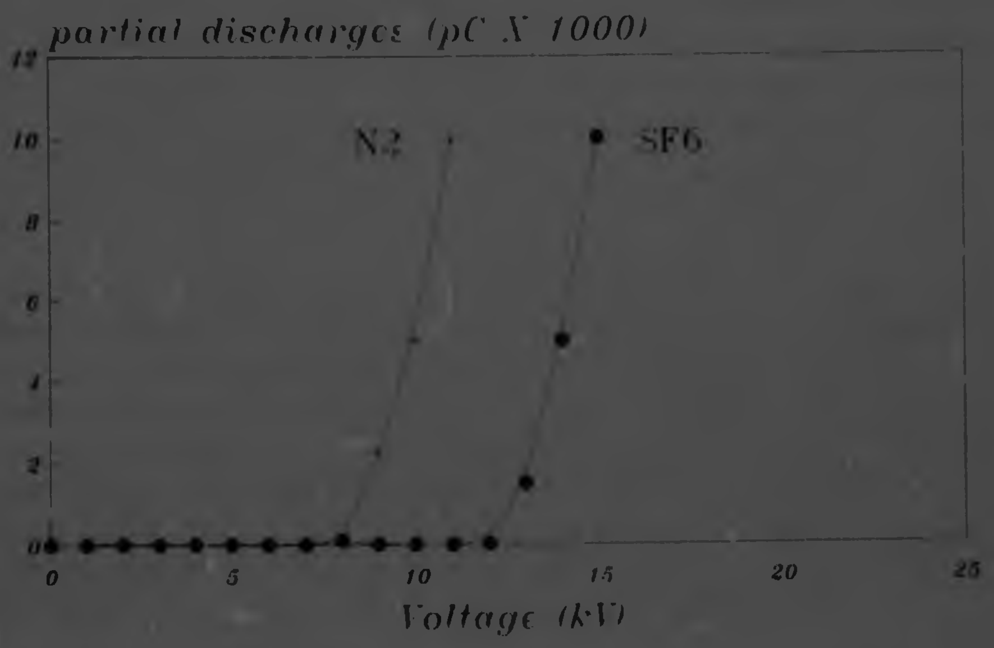
- The inception voltage for large discharges (> 500 pC) in N_2 was a great deal lower than that for SF_6 (10 kV compared to 14 kV).
- The voltage at which flash-over took place when N_2 bubbles were present was lower than that at which it took place when SF_6 bubbles were present (12 kV compared to 16 kV).
- It was seen that the extinction voltage for partial discharges in N_2 bubbles was about 20% - 35% lower than the inception voltage. This is compared to SF_6 where the extinction voltage was only 0% - 10% lower than the inception voltage.

Partial discharge tests taken to breakdown comparing SF_6 and N_2 bubbles

Table 4.2

Voltage kV	partial discharges in trapped SF_6 bubbles (pC)		partial discharges in trapped N_2 bubbles (pC)	
	magnitude	comment	magnitude	comment
1	0	-	0	-
2	0	-	0	-
3	0	-	10	occasional small discharges
4	0	-	10	same as above
5	5-10	small intermittent discharges	10	same as above
6	0	-	10	same as above
7	0	-	10	same as above
8	0	-	10	"
9	10	small discharges	10	"
10	10	small discharges	1000-3000	regular prolonged discharges
11	0	-	3000-5000	larger and more prominent discharges

12	0	-	> 5000	breakdown took place after 1/2 hour
13	10-50	occasional larger discharge		
14	1000-2000	large infrequent discharges		
15	2000-5000	regular but very intermittent discharges		
16	> 5000	regular discharges and then breakdown		



PARTIAL DISCHARGE ACTIVITY
N_2 Vs SF_6

Figure 4.4

The results in table 4.2 describe the events that took place in two tests where the test voltage was only taken to inception voltage and then monitored for two hours.

The most significant observation was that once the inception voltage occurred partial discharges took place continually in the case of N_2. In the case of SF_6 once inception of partial discharges took place these discharges were intermittent. There were phases when they were continuous (30 seconds - 2 minutes) and then phases when discharges did not occur (3-10 minutes). This activity was monitored for two and a half hours. Toward the end of this time the times between the cycles of partial discharge were smaller and the partial discharges were seen continually for longer periods. This effect was noted repeatedly in previous and subsequent experiments, in both cases (SF_6 and N_2)

The most consistent results were obtained when the bubble was trapped rather than bubbled quickly thus removing it frequently from its trapped position. When the bubbles were moved vary quickly into and out of their trapped positions the partial discharge inception voltages were higher than when the bubbles were trapped for long intervals between the paper insulation. In these cases the inception voltage tended to be higher than for the cases where there were trapped bubbles. A set of experiments, was repeated at least three times, usually more.

Partial discharge tests taken to inception voltage and monitored for a length of time after the inception of the discharges

Table 4.3

Voltage kV	partial discharges in trapped SF_6 bubbles (pC)		partial discharges in trapped N_2 bubbles (pC)	
	magnitude	comment	magnitude	comment
1	0	-	0	-
2	0	-	5	very occasional very small partial discharges
3	0	-	0	-
4	0		10-20	infrequent groups of partial discharges
5	20	small bursts of discharges	20-50	one burst of larger discharges noted
6	20	infrequent regular discharges	"	"
7	20	very occasional discharge	20	regular discharges & more continuous
8	0	-	20	slightly larger and more frequent

9	20	very occasional short burst of discharges	20	again more continuous than previously
10	20-1000	one set of discharges noticed	20	nothing exiting
11	20-100	not much	/	/
12	"	"	> 2000	continual large discharges
13	20	very occasional large discharges & regular small discharges	-	no readings taken at this voltage or beyond
14	20	continuous regular discharges	-	
15	1000-2000	continuous discharges followed by a break and then continuous discharges again	-	

4.4.1 Bubble behaviour

When (SF_6) bubbles were channelled between two plate electrodes, which were at high voltage, the following was noted. The bubbles moved slower through the liquid between the electrodes than they did when there was no voltage. It should be noted that the two electrodes were closer at the top than the bottom causing a non-uniform field which probably had some effect on the bubble motion. When bubbles were moving very quickly between the plate electrodes and breakdown took place across a bubble the breakdown was not always sustained across the gap.

Partial discharge activity in slow and fast moving N_2 bubbles

Table 4.4

Voltage kV	Partial discharge activity with very slow bubbling of N_2 in stressed region (pC)		Partial discharge activity with fast bubbling of N_2 in stressed region (pC)	
	magnitude	comment	mag.	comment
1	0	-	0	-
2	0	-	0	-
3	0	-	0	-
4	10	some small partial discharges detected	0	-
5	10	infrequent mostly very small partial discharges	0	-
6	0	-	0	-
7	20	a few more discharges seen than before	0	-
8	10-20	same as above	< 5	very small partial discharges
9	20	infrequent bursts of discharges	10	infrequent small discharges

10	"	"	10	regular small partial discharges
11	1000-3000	continuous large discharges	0	-
12	-	no more readings take at this voltage and further	0	-
13	-	"	0	-
14	-	"	10-100	regular small discharges & a few bigger ones

4.5 Conclusions

The following points can be made succeeding the tests which have been conducted and the results obtained.

- Trapped SF_6 bubbles exhibit superior partial discharge limiting and quenching attributes when compared with N_2 bubbles. This is assumed to be due to the electronegativity displayed by the SF_6 compared to N_2 which is not an electronegative gas.
- Bubbles which were moving quickly through the stressed region did not exhibit as much partial discharge activity in them compared to bubbles trapped in the stressed region.

- While it is obvious that any bubbles present in a highly stressed region are extremely undesirable and thus it would be best if there were no gas present in the liquid, there was no proof obtained that SF_6 was any more deleterious than any other gas present in the liquid insulation.

The significance of the effect of by-products from partial discharge activity in SF_6 bubbles in insulation liquid has been emphasised. It has been stated (Yamashito and Mori, 1975), (Bakale and Shmidt, 1981) that ordinary SF_6 dissolved in mineral oil was not found to be a problem as far as the dielectric strength is concerned. When SF_6 bubbles in the oil undergo corona, however, the decomposition products are found to reduce the dielectric strength of the oil. Because of the significance of chemical by-products of SF_6 in liquid insulation as regards the dielectric strength and life of the insulation it seemed suitable to present a brief section on the by-products of SF_6 and some of the chemical reactions involved.

5.1 Decomposition products of found after partial discharges in SF_6

One of the products produced during partial discharge decomposition of SF_6 is H_2O. The initial presence of H_2O cannot be avoided in a standard experimental set-up unless stringent measures such as vacuum sealing of apparatus after high temperature baking. The water is presumably released by the surface desorption when one of the electrodes is heated by the discharges (Van Brunt and Leep, 1982). The other predominant by-products are SOF_2 and SO_2F_2. Corona induced degradation takes place in the presence of water existent in the oil so the production of water is not at all desirable. H_2O produced during partial discharge activity in the SF_6 bubbles could come from the electrode surface heating from the discharge in the gas and not directly from SF_6 decomposition. The concentrations of the oxifluorides (SOF_2 and SO_2F_2)

depends upon the partial discharge magnitude and the energy discharge. For low energy discharges $SO_2F \approx SO_2F_2$ while for arcing $SO_2F_2 << SOF_2$.

Other by-products found in reasonable concentrations were CO, CO_2, CF_4, SO_2 and OCS.

5.2 Chemical reactions

5.2.1 Formation of SO_2F_2 and SOF_2

It is postulated that these by-products are formed as follows:

$SF_6 + e^- \rightarrow SF_4 + F_2^-$	Reduction of SF_6
$SF_4 + H_2O \rightarrow SOF_2 + 2HF$	Formation of SOF_2
$3H_2O \rightarrow 6H_+ + 3O^-$	Disassociating of water
$SF_6 + O^- \rightarrow SOF_4 + 2F^-$	Formation of SOF_4
$SOF_4 + O^- \rightarrow SO_2F_2 + 2F^-$	
$SOF_4 + H_2O \rightarrow SO_2F_2 + 2HF$	Formation of SO_2F_2

5.2.2 Reaction with copper

When SF_6 is decomposed in the presence of copper the following reaction takes place:

$SF_6 + Cu \rightarrow SF_4 + CuF_2$	SF_4 is an important by-product and reacts quickly, thus it is not detected

A similar reaction to the one described above is expected when SF_6 combines with aluminium

5.3 Conclusions

It is SF_4 which reacts with the metal oxides to form by-products. Some of the by-products have been noted to be toxic. The fluorides and sulphur dioxide are pollutants and regarded as being damaging to human health.

While it is of the opinion that the by-products of partial discharge activity in SF_6 are not desirable in insulating liquid and might attack the insulation, this question remains largely unanswered by the tests carried out during this research. The tests conducted provided no evidence of by-products attacking insulation and it was seen that the actual partial discharge activity was the reason for the degrading of this insulation. Based on this finding it can be said that the partial discharge activity would be as damaging or more deleterious over the long term than the by-products of these discharges.

Chapter 6 : Conclusion

Investigations were done regarding the gas content and the gas evolving or absorbing properties of air and SF_6 saturated insulating liquids. The results of these studies show the increasing evolution of gas corresponding with increasing temperatures in the liquids investigated (transformer oil and silicone liquid).
It was seen that SF_6 saturated transformer oil and silicone liquid evolved a greater volume of gas when compared with the same liquids saturated with N_2 and tested under similar conditions. This concurs with the recognition that SF_6 has a higher solubility in transformer oil than air or N_2 does.
In addition, it was seen that when paper insulation is present it is the predominant source of gas evolved, even at relatively low temperatures (ie 60°C or below).

It was found that silicone liquid evolved a greater amount of SF_6 than transformer oil. This indicates a greater solubility of SF_6 in silicone liquid. This supports other results which show silicone liquid as having a markedly superior partial discharge quenching capability when compared with transformer oil.

It was ascertained that both silicone liquid and transformer oil saturated with SF_6 show some significant partial discharge quenching tendencies, especially when compared to N_2 which did not exhibit any such tendencies. Sealed samples of the liquids, transformer oil and silicone liquid, saturated with SF_6 demonstrated a strong capacity for reducing the magnitude of partial discharge activity due to the gas present in the saturated test samples infiltrating into the air filled cavity.
Additionally, the results presented have provided evidence that SF_6 present in the liquids tested is not as injurious to the insulation when compared with other non-electronegative gasses. Any damage and

flash-overs observed during testing were seen to be due to the partial discharges taking place in gaseous bubbles. On the basis of the results obtained it can be seen that partial discharges themselves are more detrimental than chemical by-products, which might have a adverse long term effect on the integrity of the insulation.

Since gas in transformer oil and other liquids cannot be avoided in many circumstances, though that would be the ideal, the presence of SF_6 has some beneficial implications especially with respect to partial discharge extinction. It was seen that trapped SF_6 bubbles in highly stressed regions exhibited diminished partial discharge activity and in some cases the partial discharges were completely extinguished. It is suggested that SF_6 used in the place of N_2 above the oil in sealed high voltage equipment, such as transformers would diminish or get rid of any partial discharges completely thus lengthening the life-span of the equipment as well as reducing the possibility of failure. Of course the question which must be answered is: Will any possible long term chemical effects neutralise or overshadow any desirable partial discharge quenching properties?

The work presented here has answered some of the questions as to the effects of the presence of SF_6 bubbles in liquid insulation and pointed out some positive aspects regarding the presence of SF_6 in silicone liquid and transformer oil. Investigations are still needed to specify more clearly what chemical by-products of SF_6 are detrimental to the insulation and to what degree they will affect it, especially in the long term.

APPENDIX A

Description of apparatus used in gassing experiments discussed in chapter 2

Brass Electrodes

The high voltage electrode, with a length of 140 mm and a diameter of 10 mm, was made out of brass. This electrode had a 5 mm entrance hole at the top and a 1 mm exit hole, at the other end, for bubbling gas through liquid samples in the gassing-cell. The tip of the electrode, which was inserted into the liquid sample, was rounded. The high voltage electrode was placed into the gassing-cell via an airtight hole (sealed with petroleum jelly) in the rubber stopper used for sealing the gassing-cell. A ground electrode was made out of thin shimstock and wrapped around the outside of the gassing cell.

Gas Supply

The gas that was filtered through the liquid sample being tested was fed from a gas canister via a 1/4 inch ball valve attached to the inlet hole of the brass rod. This valve and that of the gas canister enabled the regulation of the gas flow through the liquid. Ideally the gas was bubbled through as slowly as possible in order to maximize the likelihood of the gas being absorbed by the liquid sample.

Oil Bath

The oil bath was made from a large circular transparent bottle with the top cut off and was capable of holding ≈ 16l of oil as well as components of the apparatus submersed in the oil. Shell Diala-B transformer oil was used in the oil bath. The gas burette and gassing-cell were held in place in the oil bath by a specially constructed fibreglass stand. Fibreglass was used for this stand as this material would minimize contamination of the oil in the bath as temperature cycling took place. The temperature cycling caused the oil to become acidic and it had to be replaced quite often as the visibility of the gas burette and the gassing-cell through the oil became poor, making the taking of readings impossible. Ideally silicone liquid should have been used in the oil bath but its high cost prevented this.

Temperature Regulation Apparatus

It was required to heat the test samples in the gassing-cell from room temperature to various temperatures up to 140°C and to maintain these temperatures.

A 650 W geyser heating element was used to heat the oil bath. The heating element was suspended in the oil bath via a U shaped glass rod made for this purpose.

A 6 mm diameter, 150 mm long, iron-constantin thermocouple, with a PVC lead, which can detect temperatures up to 200°C quite accurately, was used as the temperature sensor.

An on/off temperature controller made to work in conjunction with the iron-constantin thermocouple was used. This temperature controller had a range of 0° - 200°C operating from a 220 V AC supply. This temperature controller was stated to be accurate to within 1%-2% . A 220 V AC relay with a maximum current handling capability of 10 Amp was used to protect the temperature controller.

The temperature control equipment had a time lag which gave rise to a temperature variation of ± 5% at a temperature setting of 120°C . At lower temperatures this variation was less. The accuracy of the temperature control equipment was ascertained by measuring the oil-bath temperature with thermometers and comparing these values with the settings of the temperature controller.

Liquid Circulation

It was necessary to circulate the oil of the oil bath to ensure the uniformity of temperature distribution throughout the oil bath. A stirrer was made using a wooden shaft with holes at the end through which wire was looped. This shaft was connected to a windscreen wiper motor suspended above the oil bath which ensured the slow and steady circulation of the oil in the oil bath, as was desired. A 12 Volt 5 Amp power supply was used to supply the motor. The power supply needed a 120V input. This was provided by a variac used to step-down the mains supply to the power supply.

Stand

The whole set-up was placed on a two-shelved stand with the oil-bath on the lower tier. The stirrer motor as well as the temperature control equipment was placed on the upper tier connecting to the lower level via apertures in the upper shelf.

Liquid Components

- An industrial solvent was used to clean the glass and other equipment after a test.
- The marker fluid used in the gas burette was dibutyl pthalate as specified in the British standards
- The mineral oil used for the tests was Shell DIALA B-SA transformer oil
- The silicone liquid used was DC 200/100

APPENDIX B

Experimental method for gassing tests

The samples were heated up to a particular temperature at which they were maintained for a given length of time and the gas absorbing or evolving trends were noted before the oil bath was heated up to the next temperature. Due to the comparative nature of the tests each sample under comparison was maintained at each temperature for the same amount of time as the other samples with which they were being compared. The decision on how long to monitor the situation at each temperature depended on the gassing activity at that temperature i.e. usually the situation was monitored until there was minimal gassing and then left for an additional half hour. If after that half hour there was $< 100\ mm^3$ of gas evolved or absorbed then the temperature controller was set to the next level. This method allowed for the calculation of the amount of gas produced or absorbed at any particular temperature.

The stopcock on the gas burette was opened every half hour for some experiments while for others it was opened as seldom as possible. The reason for opening the stopcock was to prevent pressure building up and influencing the results. In the cases where the stopcock was left unopened the effect of the column pressure above the samples on their gassing was monitored

Since the gassing tendencies of the liquids may be strongly influenced by the presence of solvents care was taken to clean out the gassing-cell and gas burette assembly before each test was conducted. All sealing to make the glassware airtight was done using petroleum jelly.

While it is difficult to quantify the gassing properties of a particular sample the most meaningful use of the results obtained was of a relative nature. When two or more samples were being compared every effort was made to duplicate the experimental conditions and the method of experimentation for these comparative purposes.

There are several factors which might have influenced the gassing results and these factors had to be taken into consideration.

Atmospheric Humidity

It was suspected that the atmospheric humidity would have an influence on the results. Tests performed on humid days might produce differing results to those produced on less humid days. If there are humid conditions a sample will have a higher moisture content and moist liquids tend to evolve gas more readily, however, this is a long term effect (an insulating liquid exposed to moist atmosphere will need > 20 days for the full effect to be felt). Since the samples had been exposed to the same atmospheric conditions this effect was ignored as far as these comparative experiments were concerned.

Atmospheric Pressure

Atmospheric pressure is not constant and there are day to day variations which might have some effect on the gassing. This factor was monitored and it was concluded that the variations in atmospheric pressure were small enough so that they could be effectively ignored.

Pressure Exerted By Marker Liquid and Gas Above Test Sample

Another pressure effect was that exerted by the gas evolved by the test liquid. As gas is evolved from the liquid being tested the pressure exerted by the column of marker liquid and the gas above the test sample increases thus decreasing further gas evolution or even causing re-absorption of gas already evolved from the liquid. This effect was taken into account by using a consistent amount of marker fluid as well as using consistent measurement methods (ie. when to open stopcock etc.) to ensure that the comparative results were as accurate as possible.

Room Temperature

The room temperature, at which the experiment took place, had some effect on the results obtained when heating up to the first measurement temperature. In order to nullify this effect all the samples were heated up to 30°C before a test commenced. The room temperature had some effect on the time taken in heating or cooling samples but this was regarded as having little effect on the results obtained.

Air Expansion

The amount of air expansion (or contraction) that took place due to the change in the temperature of the gas above the sample was approximated by experimental observation as well as by calculation and this increase was subtracted from the registered change in the height of the marker fluid. A problem that did occur was that the whole of the gassing-cell was not submerged in the oil bath, so it was impossible to accurately measure the temperature of the air, above the sample, in the sealed cell. The assumption was made that the heat transfer properties of the oil-bath and the air and liquid in the gassing-cell allowed the air above the level of the oil in the oil-bath to be maintained at the same level as that of the oil bath.

Liquid Expansion

The expansion (or contraction) of the marker liquid in the gas burette were noted by opening the stopcock of the gas burette at every temperature of measurement so that this factor could be taken into account. The liquid expansion of the test sample was also observed.

APPENDIX C -- Tables of Gassing Results

Table 2.1 - Gassing results at 60°C

TIME hours	Transformer oil mm^3	Air saturated silicone liquid mm^3	SF_6 saturated transformer oil mm^3	SF_6 saturated silicone liquid mm^3
0.0	0	0	0	0
0.5	550	275	196	177
1.0	177	648	450	1512
1.5	39	700	668	1806
2.0	-255	746	648	1924
2.5	-452	825	864	2042
3.0	-530	884	1021	2101
3.5	-628	962	1060	2179
4.0	-628	1001	1158	2238
4.5	-648	1100	1198	2317
5.0	-726	1100	1060	2415

Table 2.2 - temperature related gassing of three insulation liquids

Temperature °C	gassing of transformer oil mm³	gassing of silicone liquid mm³	gassing of a perchlor-ethylene Midol combination mm³
30	59	-20	-18
60	314	196	942
90	825	1050	4418
120	1669	2461	12134

Table 2.3 - transformer oil vs silicone liquid

Temperature $^\circ C$	Transformer oil gassing mm^3	Silicone liquid gassing mm^3
30	-177	-39
60	-1	158
90	1079	787
120	1163	1913

Table 2.4 - gassing of transformer oil

Temperature $°C$	Air saturated transformer oil mm^3	SF_6 saturated transformer oil mm^3
30	-177	59
60	-1	1198
90	1079	4114
120	1499	6722

Table 2.5 - SF_6 and air saturated silicone liquid

Temperature °C	Air saturated silicone liquid mm^3	SF_6 saturated silicone liquid mm^3
30	-39	-20
60	[illegible]	765
90	787	3720
120	1874	7293

Table 2.6 - heating cooling tests

Temperature °C	gassing of unsaturated transformer oil mm^3	gassing of air saturated transformer oil mm^3	gassing of silicone liquid mm^3
30	-275	-79	-79
60	-432	1571	137
90	-157	1944	1031
120	2755	2022	1708
90	-1860	1870	1041
60	-2654	-1345	331
30	-2859	-633	1589

Table 2.7 - Gassing of liquids in the presence of paper insulation

Temperature °C	gassing of air saturated mineral oil with paper mm^3	Gassing of air saturated silicone liquid with paper mm^3	gassing of SF_6 saturated mineral oil with paper mm^3	gassing of SF_6 saturated silicone liquid with paper mm^3
30	-177	0	137	157
60	432	1590	1532	962
90	3711	4506	5733	5321
120	6754	9052	9981	10492

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