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Hydrogen gas-in-oil on-line monitor for high voltage current transformers.

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HYDROGEN GAS-IN-OIL ON-LINE MONITOR FOR HIGH VOLTAGE CURRENT TRANSFORMERS

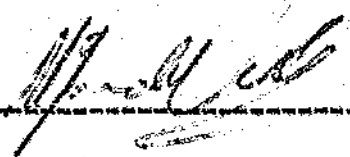
M. J. Van de Venter

A dissertation submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 1991

DECLARATION

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



2nd day of MARCH 1992

ABSTRACT

The sudden failure of oil paper-insulated current transformers has become a problem of considerable concern due to the cost of the resulting destruction, and danger to personnel. The aim of the dissertation is to determine the most suitable method of detecting incipient faults in current transformers, test this method on an experimental current transformer, and finally implement this technique in a low cost on-line monitor. A literature survey indicated that hydrogen gas-in-oil on-line monitoring would be the most suitable technique.

In the design and testing of a hydrogen on-line monitor, different types of hydrogen sensors were evaluated. A reliable, accurate and low cost hydrogen sensor at the time of investigation could not be obtained. The on-line monitor employed a membrane to separate the dissolved hydrogen gas from the oil. This proved unreliable. A similar commercial design was shown be temperature sensitive due to the similar technique used. Therefore a cheap and reliable on-line monitor using a membrane has not been found.

The experiments performed on the experimental current transformer proved that testing for hydrogen gas in the air space above the oil is a reliable method for detecting incipient faults. The mounting position of the on-line monitor is critical. Standard sampling tins proved unreliable for determining the hydrogen concentration in the oil.

DEDICATION

To my lovely wife, Lesley,

and my parents

for all their support.

ACKNOWLEDGEMENTS

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1 INTRODUCTION

The sudden failure of oil paper insulated current transformers has become a problem of considerable concern. While the number of failures as a percentage of the total number installed may not be high, the failures themselves are disruptive to the system and extremely hazardous. Chunks of porcelain can be flung up to 100 metres from the offending transformer, putting staff and equipment at considerable risk. In a comprehensive study undertaken by the Tennesse Valley Authority it was concluded that the failures were the result of "generic problems in insulation quality and that the system related conditions probably did not contribute to the CT failures" [1]. Although not yet reported in the literature, experiences similar to the North American ones referred to in the references have been found in the Republic of South Africa. In support of it, evidence which is being collected in the Republic of South Africa does indicate that the failures have only occurred in particular types and designs of current transformers [2].

Research conducted by Reynders indicated that hydrogen and ethane levels are an effective means of assessing the e .t of the partial discharge ageing [2]. A project was initiated by Prof. J.P. Reynders at the University of the Witwatersrand to build a low cost hydrogen monitor for current transformers, and then test this principle on an experimental tank. This formed two natural avenues of research. The first part of the research is to design and build a low cost on-line monitor. The second part involves testing the principle of hydrogen gas-in-oil on-line monitoring, using either the on-li monitor built or an alternative method.

1.1 Preview of rest of the dissertation

This MSc(ENG) dissertation has been divided into four parts. The first part is this document, which is a summary of the other three parts, appendixes A, B and C. Each appendix has been written as a self-contained document.

Chapter 2 gives a short review of the different methods that can be used for on-line monitoring. This is used to present a strong case for using hydrogen gas-in-oil monitoring for detecting incipient faults, as opposed to other methods. The previous work done on hydrogen monitors is then given. For more information see Appendix A.
The specific aims of the MSc(ENG) dissertation are then listed.

Chapter 3 has a short description of all the experimental apparatus used. This is a summary of Appendix B.

Chapter 4 first gives the background of the experiments, and then in turn briefly describes each experiment. For complete information on these experiments see Appendix C.

Finally the conclusions that can be made from these results are presented and recommendations for future work are given.

Appendix A consists of the literature survey which ascertains the current state of art in gas-in-oil (GIO) analysis and on-line monitors. Appendix A should prove invaluable to somebody who requires a comprehensive summary of GIO analysis techniques for transformers and on-line monitoring techniques.

Appendix B consists of a description of all the apparatus used to perform the experiments. This appendix will prove useful for anybody continuing research into this field, and will be using the apparatus already built, or improving on the apparatus designed.

Appendix C contains a description of all the experiments performed. This appendix will be of primary interest to somebody continuing the research or requiring the latest information on the current state of art in gas-in-oil on-line techniques. Some of the experiments also will be of interest to those involved in general gas-in-oil techniques.

2 FORMULATION OF THE PROBLEM

2.1 Failure in oil-filled current transformers

The insulation system of a high voltage current transformer must be designed to cope with high electric field. This is done by grading the field with capacitive screens, and by using a large body of paper insulation which needs to be impregnated with mineral oil. Areas of high local stress can still occur at the edges of the capacitive screens. Because of the localization of these areas of high stress, they do not adversely affect the overall insulation strength and the current transformer will pass standard over-voltage tests. The high localized stress will, however, cause partial discharges, and the associated electro-chemical activity will result in a slow, but sustained, deterioration of the insulation. The situation can also be aggravated if impregnation with the oil is inadequate. The paper insulation around the high tension conductor is, depending on the service voltage, tens of millimetres thick. The paper is usually tightly wound and inadequate impregnation can result in low pressure voids at high field areas deep within the insulation. Partial discharges will commence at such a defect and cause slow deterioration of the insulation.

A latent defect such as those discussed above may be dormant, in that, service stress levels are not adequate to cause partial discharges. However, a temporary over-voltage may initiate discharge activity at the site which will then be maintained at service voltages.

Partial discharge activity causes decomposition of the oil and the paper, and in this way releases hydrocarbon gases which are absorbed in the oil. Partial discharge activity can therefore be monitored by conventional electrical detection methods, or by monitoring the gases which are dissolved in the oil.

2.2 Overview of the current methods to check incipient faults

2.2.1 Partial discharge measurement

The breakdown of high voltage solid insulation in service by electric treeing or tracking is preceded by a period of emission of partial discharge pulses. There are a number of standard laboratory methods for measuring partial discharge activity in transformers. In the past nearly all such diagnostic testing required costly temporary removal of the equipment from service. Partial discharge testing done during normal operation was considered impossible due to the interference from the much greater electrical noise signals caused by the power line carrier, radio stations, transmission line corona, breaker operations, etc.[4] Also, for some insulation systems, the time between the onset of detectable partial discharge and catastrophic failure could be too short for the condition to be detected by a practical economic periodic test procedures.[3]
A Fault Anticipator for Substation Equipment (FASE) system has been developed that can detect and identify a partial discharge in a noisy substation environment.[4] Ferrite cores, which are sensitive to partial discharge pulses, are placed around the ground leads of the current transformers . The outputs are connected to a common controller which records the partial discharge pulses and their directi n. Noise pulses on the system bus will be picked up at all the current transformers and thus rejected. However if one current transformer consistently produces a pulse of opposite polarity to that from all the current transformers, it is identified as being in trouble. Unfortunately this technique is only suitable for current transformers connected to a common bus. The time interval between partial discharge onset and failure may vary from a few minutes to thousands of hours, depending on the local stress enhancement, and the nature of the insulating system. [4] Also more importantly, there is no direct relationship between the rising partial discharge activity and insulation deterioration.

The experiments performed at the CSIR indicate that while the hydrogen level in a current transformer continued to rise due to a fault, the partial discharge activity remained relatively constant. [2]

2.2.2 Acoustical techniques

The ageing of electrical insulation material is connected with structural degradation and molecular changes. The energy content varies and besides quantum emission also phonon excitation and propagation occurs. Partial discharges will result in acoustical emission. Depending on the amount of disengaged energy a sound detection is possible. An acoustical analyser has been built that can automatically distinguish between hot spots in solid and liquid insulation, partial discharges, mechanical crack initiation and propagation.
But further investigations will have to be carried out in order to find solutions for analysing superpositions of two or more sources with different intensities.[5] Because this technique is still in its infancy, its usefulness for on-line monitoring is still limited.

2.2.3 Power factor measurement

The power factor of electrical insulation has been recognized as a good indicator of its quality and future serviceability. Almost any form of degradation of the insulation will, sooner or later, increase its power factor. A common practice in the industry has been to periodically take the equipment out of service, and measure its power factor and capacitance. Recently a microcomputer based apparatus has been developed which monitors power factor and capacitance continuously, with the transformer on-line. Initial tests done on current transformers indicate that it provides an indication of a possible incipient fault. Further testing still has to be done to confirm that a rising power factor is a definite indication of an incipient fault.

The first limiting factor with this method is that the apparatus only works on transformers with a capacitance tap.[6] Secondly, power factor measurement is a bulk phenomenon. Power factor change due to localized discharges could be obscured by the overall measurement. This is supported by the work done by Reynders and Meal. While a rising hydrogen concentration indicated a fault in a current transformer, the power factor remained relatively constant, though it was high. [2]

2.2.4 High performance Liquid Chromatography technique

Recently some transformers have failed due to slight overheating at 110 - 120 degrees Centigrade. Gas analysis cannot differentiate between that and general oxidation. High Performance Liquid Chromatography has been used to separate hydrocarbon compounds produced exclusively by thermal degradation of paper at temperatures from as low as 110 degrees Centigrade. The presence of furfuraldehyde has shown positive correlation to increases in paper insulation overheating.
High Performance Liquid Chromatography analysis lacks the sensitivity of Gas-in-Oil analysis. Also building a simple and cost-effective on-line monitor based on HPLC techniques will be impossible with the present state of art. It remains a sophisticated laboratory technique.[7]

2.2.5 Gas-in-oil analysis

Gas-in-oil analysis as opposed to the other techniques is well proven and reliable in determining the condition of the insulation. For the complete range of temperature faults, the transformer oil will decompose to its constituent molecules, slowly for low temperature faults (overheating) and rapidly for high temperature faults (arcing).

A chemical model of this reaction shows that hydrogen gas will be produced by all the faults, and in larger quantities than the other faults. Rising hydrogen level is an excellent indication of an incipient fault.[8] By checking only for hydrogen gas, the potential cost of the instrument can be kept down.

Note : See Appendix A for the complete literature survey to support hydrogen gas-in-oil monitoring.

2.3 Review of the previous work

The first hydrogen monitor was developed by Hitachi. It used a membra to separate the dissolved hydrogen gas from the oil. Reported results are encouraging. One problem with the design was that the hydrogen concentration was only measured every 72 hours![9] A fault could easily develop in this time, and not be detected by the apparatus before the transformer failed. This monitor also has not been available for purchase to the best of the my knowledge.
A hydrogen monitor (product name omitted intentionally) is available commercially at a cost of approximately R40 000 in S.A. This is far too expensive for wide usage on CTs. The cost of current transformers start at approximately R8 000. One problem with the commercial on-line monitor is that alarms can only be set for absolute readings. Due to the varying amounts of gas normally present in the transformers, an alarm could be triggered for a transformer that is operating satisfactorily. It is better to trigger an alarm on a large rate of increase of the hydrogen gas concentration in the oil.

2.4 Specific aims of the MSc(ENG) study

The aims of the MSc(ENG) study are divided into two separate avenues for research.

The aims of the study related to designing and building a low cost on-line monitor are :

1. Obtain and test suitable hydrogen sensors for the on-line monitor.
2. Obtain a suitable membrane for the on-line monitor.
3. Design and build the electronics for the on-line monitor.
4. Design and build a suitable enclosure.

The aims of the study related to testing the principle of the on-line monitor are :

1. Build an experimental tank that would allow the on-line monitor to be tested.
2. Note the response of the monitor to faults in the oil.
3. Use the on-line monitor or other means to ascertain whether the position at which the on-line monitor is bolted on, affects the results.

3 TEST FACILITY AND THE EXPERIMENTAL APPARATUS

3.1 General requirements

The overall aim of the project was to build a low cost hydrogen G.I.O. (Gas-in-Oil) on-line monitor, and use that, or some other means, to test the principle of hydrogen gas-in-oil monitoring.

This called for 3 distinct apparatus : an experimental tank, an on-line monitor, and some form of datalogging facility.

The experimental tank was designed to allow on-line monitors to monitor the hydrogen concentration in a controlled experiment. The tank allows different on-line monitors to be bolted on at various positions. A hydrogen sensor can also be bolted in the air space above the oil. Partial discharge and arcing can be induced in the oil at various heights. Alternatively, hydrogen gas can be directly injected into the oil.

The on-line monitor was built using a permeable membrane to separate the dissolved hydrogen gas from the oil. Hydrogen gas dissolved in the oil will diffuse through the membrane, and be detected with a resistive element hydrogen sensor.

When the project was initiated, it was envisaged that the datalogging side would be a large portion of the work. A prototype datalogger was built around a commercially available microprocessor board. A self-contained microprocessor board was then designed. At this stage it became clear that the problems associated with the actual G.I.O. monitoring were more important. The final product was therefore not implemented. The experiments were completed using a commercial datalogger.

Initially standard sample tins were used to take oil samples from the experimental tank. Problems were encountered with the reliability of this method for the hydrogen gas. The hydrogen gas would dissolve into the air bubbles in the sample tin, which subsequently was lost when the sample tin was opened. To eliminate any possible errors due to the sampling technique, two gas-tight syringes were used for the rest of the experiments.

At a later stage a more accurate hydrogen sensor, fuel cell hydrogen sensor, was obtained. This was used to monitor the hydrogen gas level in the air space above the oil in the experimental tank.

The gas-tight calibration chamber was built to calibrate the sensors and test the commercial hydrogen monitor.

See figure 3.1 for the complete block diagram of the experimental setup. See figure 3.2 for a photo of the complete experimental setup.

3.2 Experimental Tank

The tank consists of 4 ports to which on-line monitors are bolted on at different heights. The fuel cell hydrogen sensor can be bolted to the bottom of the top lid. This allows the hydrogen concentration in the air space above the oil to be monitored.
A partial discharge or arc can be created in the oil to simulate a fault. This can be done at any desired height in the oil. The amount of partial discharge or arcing can be monitored on the partial discharge monitor. For more accurate studies, the apparatus was modified to allow a direct injection of a known amount of hydrogen gas into the oil.

See figure 3.2 for a photo of the tank, and figure 3.3 for the diagram of the tank.

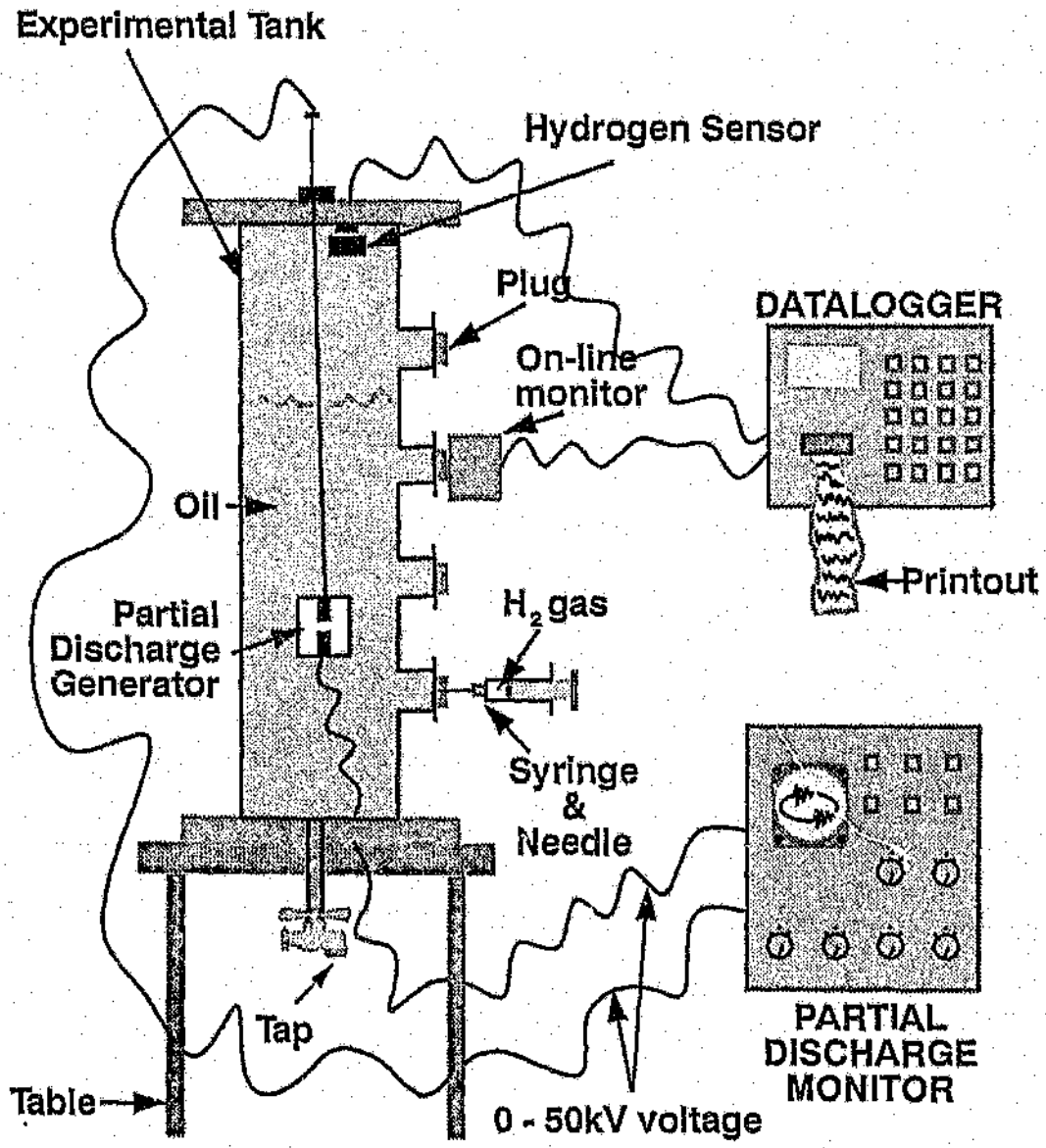


Figure 3.1 Block diagram of the complete experimental set-up

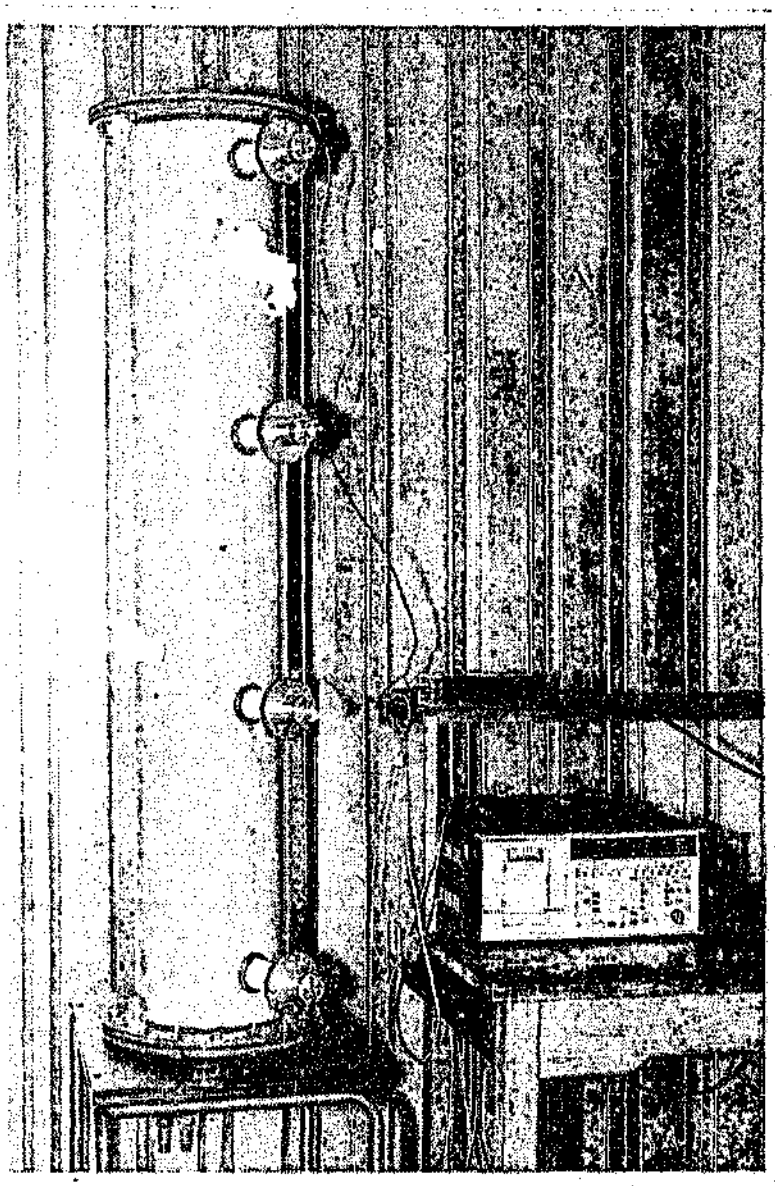


Figure 3.2 Photo of the complete experimental setup

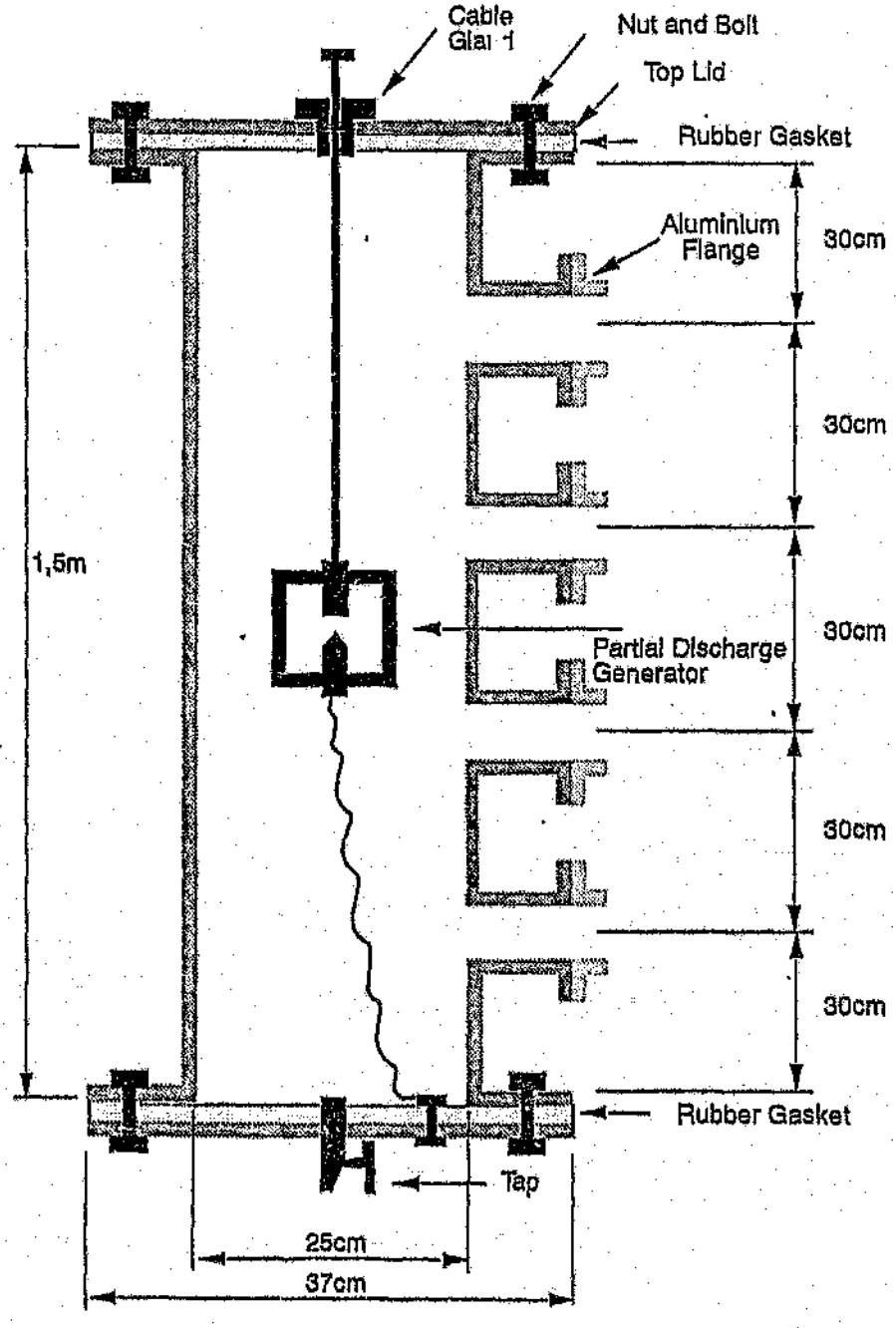


Figure 3.3 Diagram of the experimental tank

3.3 Hydrogen Gas-in-Oil Monitor

The basic principle of operation is that the gases dissolved in the oil will diffuse through the membrane into the gas chamber. Once equilibrium is reached, the ratio between the concentration of hydrogen in the oil, and in the gas chamber will be equal to the Ostwald solubility coefficient for hydrogen. Therefore the reading from the resistive element hydrogen sensor should be proportional to the concentration of the hydrogen gas in the oil.
See figure 3.4 for a cross-section of the c. line monitor, figure 3.5 for a photo of the assembled monitor.
The electronics convert the signals from the hydrogen sensor and the temperature sensor into 4-20mA outputs. See figure 3.6 for a block circuit diagram.

3.4 Gas-tight Calibration Chamber

A gas-tight chamber had to be constructed to calibrate the resistive element hydrogen sensors.
To increase the versatility of the chamber, the chamber has a port, the exact same size as one of the ports on the experimental tank. One of the aluminium flanges used on the tank, is bolted to this part. This arrangement allows the fuel cell hydrogen sensor to be screwed into this port, or via an adapter, the commercial hydrogen monitor. If this feature is not used, the port can blocked off with one of the brass plugs. The fuel cell hydrogen sensor is bolted onto the port, and the resistive element hydrogen sensors are inside.

The chamber also can be filled with oil, into which hydrogen gas can be injected. A magnetic stirrer is used to mix the hydrogen gas and the oil.

See figure 3.7 for a photo of the calibration chamber.

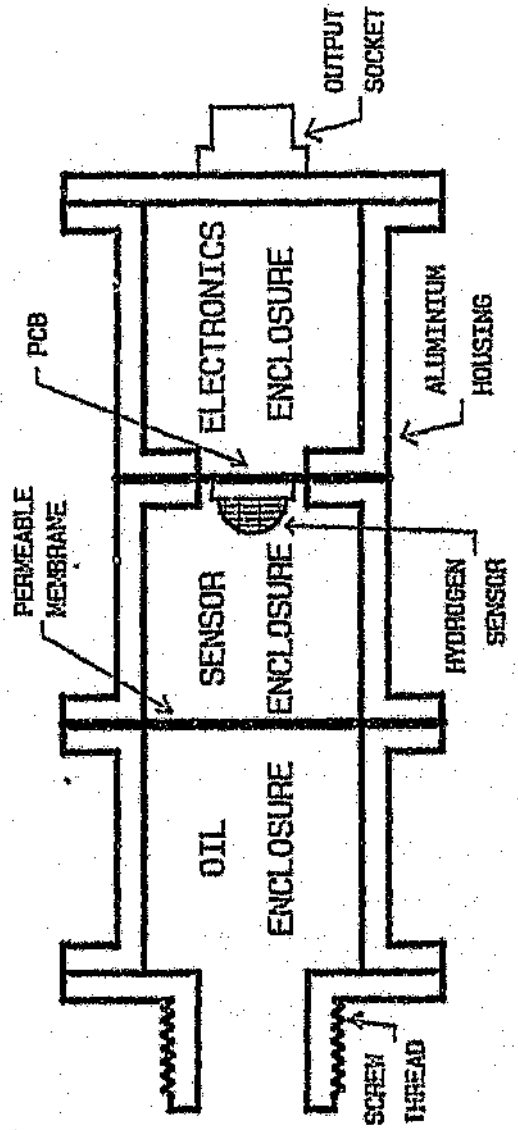


Figure 3.4 Cross section diagram of the hydrogen on-line monitor

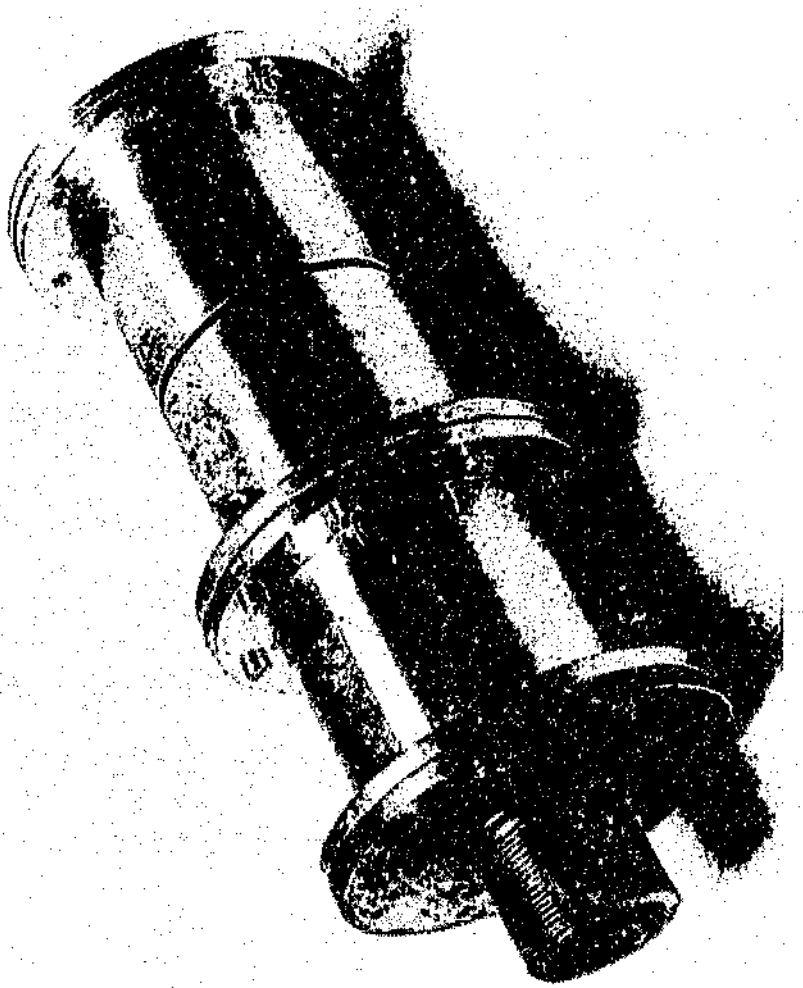


Figure 3.5 Photo of the assembled on-line monitor

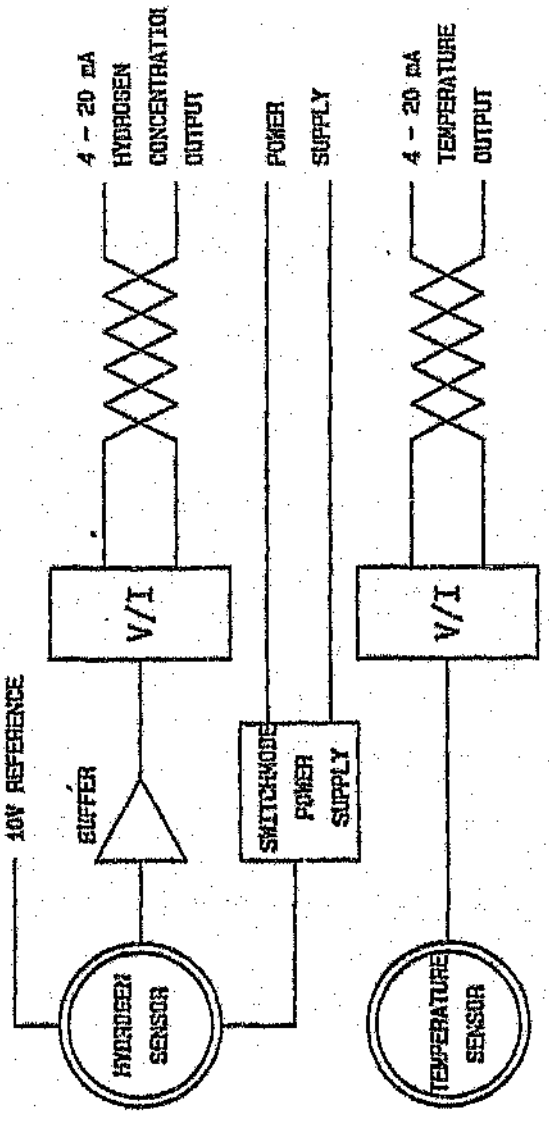


Figure 3.6 Block diagram of the sensor electronics

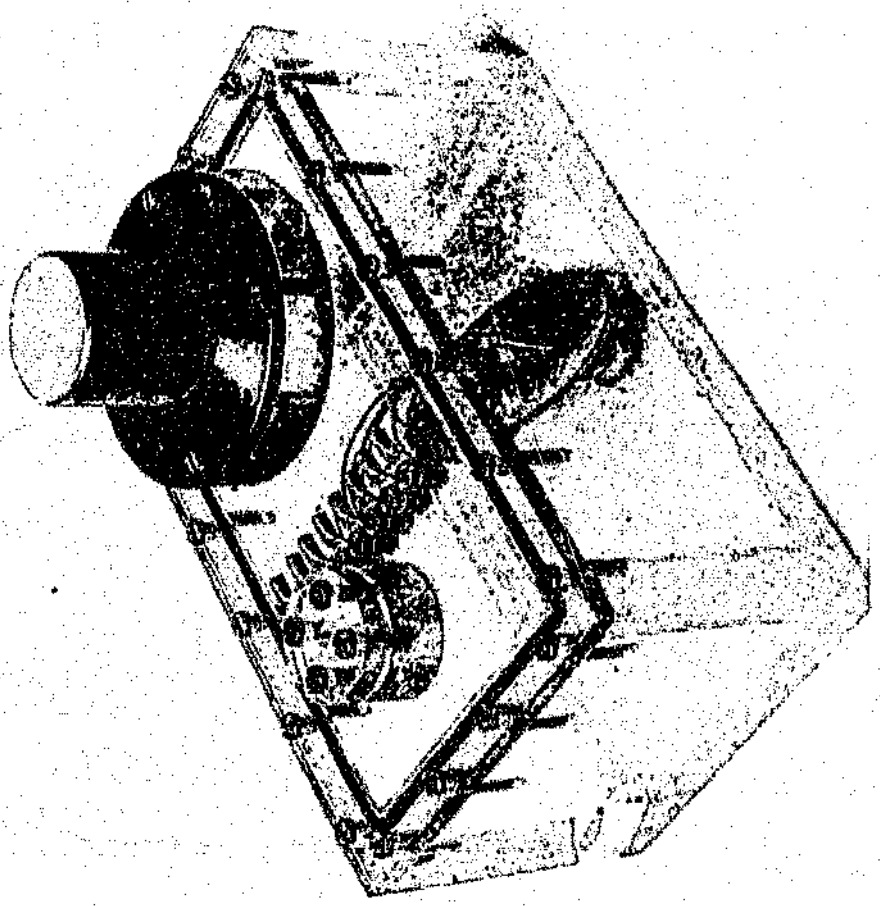


Figure 3.7 Photo of the gas-tight calibration chamber

4 EXPERIMENTAL PROCEDURE

4.1 Background

A brief description of the background of the experiments will be given. This allows the reader to understand why some of the experiments were performed.

Two hydrogen sensors were obtained. The fuel cell hydrogen is an expensive pre-calibrated and self-contained unit. The resistive element hydrogen sensor is cheap, but un-calibrated. It was anticipated that the resistive element hydrogen sensor would be used in a cheap on-line monitor.

In the first experiment, both sensors were mounted in the air space of the experimental tank. This allowed a direct comparison between the two sensors.
Oil samples were taken for laboratory analysis on a gas chromatograph, as a reference. The results indicated that there were possible problems with the sampling method for hydrogen gas. The hydrogen gas would escape out of the sample tins when they were opened. Gas-tight syringes were ordered that would provide more accurate sampling results. The oil would be injected into the gas chromatograph without direct contact with the air.

In the second experiment, the on-line monitor was tested on the tank. The results were negative. To check whether the problem lay with the on-line monitor or the experimental set-up, the commercial hydrogen monitor was used. Similar results were found. This indicated a problem with the experimental set-up or both the on-line monitors.

At this stage it was decided to calibrate the resistive element hydrogen sensors more accurately than in experiment 1. The gas-tight chamber was built. A known amount of hydrogen gas could be injected into the chamber and the output from the resistive element hydrogen sensors monitored. This forms the basis for experiment 3.

The gas-tight chamber was designed so that the on-line monitors could be tested on it. Due to the negative results from experiment 2, the commercial on-line hydrogen monitor was tested on the gas-tight chamber. The results for this experiment 4, indicated that the commercial hydrogen monitor is sensitive to external conditions. Because the designed on-line monitor is based on the same principle, it was decided to halt the development of the on-line monitor, and rather use the gas-tight syringes to complete the rest of the experiments.

At this stage the fuel cell hydrogen sensor became poisoned. The fuel cell was replaced, but unfortunately was uncalibrated. The fuel cell hydrogen sensor and the resistive element hydrogen sensor was retested. See experiment 5. This allowed a direct comparison of the two different technologies.

For experiment 6, the tank was modified to allow oil samples to be taken using the gas-tight syringes. Hydrogen gas can also be injected into the tank using a gas-tight syringe.

4.2 Experiment 1

See Chapter 2, page 5, of Appendix C for more information.

4.2.1 Purpose

Time response and comparison between the fuel cell hydrogen sensor and the resistive element hydrogen sensors in the air space above the oil in the experimental tank.

4.2.2 Method

The experimental tank is filled to 3/4 of its height with oil. The fuel cell hydrogen sensor is bolted to the bottom of the top lid. The resistive element hydrogen sensor is bolted to the top port. The rest of the tank is sealed.

Arcing of various time lengths was induced in the bottom of the tank. The output from the fuel cell hydrogen sensor and the resistive element hydrogen sensor was monitored using a datalogger. Oil samples from the bottom of the tank was taken after a few hours from the start of the arcing.

4.2.3 Results and conclusions

1. The fuel cell hydrogen sensor responds to a fault in the bottom of the tank within 1 minute, and reaches a steady reading within 15 minutes. See figure 2.1, page 9, of Appendix C.

2. The resistive element hydrogen sensor responds to a fault in the bottom of the tank within 2 minutes, and reaches a steady reading within 20 minutes. See figure 2.2, page 10, of Appendix C.

3. Assuming the fuel cell hydrogen sensor is accurate, the resistive element hydrogen sensor response is not linear. There is also a spread in the reading. There is approximately a maximum of a 125ppm spread for any particular voltage reading. See figure 2.3, page 13, of Appendix C.

4. The hydrogen concentration in the air space is not proportional to the hydrogen concentration in the oil, but is proportional to the acetylene concentration in the bottom of the oil. The acetylene dissolves relatively easy in the oil compared to the hydrogen. When an oil sample is taken, if the sampling tin is not perfectly sealed, the hydrogen will escape. I believe that unreliable sampling techniques account for the erratic results for hydrogen concentration in the oil. See figure 2.4, page 15, of Appendix C.

5. The hydrogen concentration in the air space is proportional to the duration of the fault. See figure 2.5, page 17, of Appendix C.

4.3 Experiment 2

See Chapter 3, page 20, of Appendix C for more information.

4.3.1 Purpose

Tests, in contact with oil body in the experimental tank, with on-line monitor and the commercial hydrogen monitor.

4.3.2 Method

The experimental tank was filled to 4/5 ths of its height with oil. The on-line monitor was bolted to the top port, and was in contact with the oil. Arcing was induced in the bottom of the tank. The commercial on-line monitor was then bolted to the top port and the test repeated.
The tank was then filled to the top with oil and the tests repeated.

4.3.3 Results and conclusions

1. Both the on-line monitor and the commercial hydrogen monitor indicated that the no dissolved hydrogen gas has been detected at the ends of the ports. Either both the on-line monitor and the commercial hydrogen monitor were not operating correctly, or the hydrogen in the oil was not reaching the ends of the ports. Since both monitors were not operating correctly, it was suspected that the hydrogen was not reaching the ends of the ports.

4.4 Experiment 3

See Chapter 4, page 23, of Appendix C for more information.

4.4.1 Purpose

Calibration of the resistive element hydrogen sensors.

4.4.2 Method

Three resistive element hydrogen sensors were sealed in the gas-tight calibration chamber. Various concentrations of hydrogen gas was introduced into the chamber. The results were monitored on a datalogger.

4.4.3 Results and conclusions

1. Resistive element hydrogen sensor 1 and resistive element hydrogen sensor 2 show good repeatibilty for all the tests, except for test 4. In the fourth test the readings are totally different. The sensors were cold at this stage. This implies that the sensors are accurate only if the sensors are allowed to reach an equilibrium temperature. See figure 4.1, page 26, of Appendix C.

2. The repeatibilty of resistive element hydrogen sensor 3 is poor for a 500ppm concentration of hydrogen. Sensor 1 and 2 were new sensors when the above tests were performed on them. Sensor 3 had been used approximately for a year before this. This implies that the accuracy of the resistive element hydrogen sensors possibly deteriorate as they age. See figure 4.3, page 32, of Appendix C.

3. To compare the three sensors, the differences in the minimum output voltage for each sensor at the two different concentrations are taken. For sensor 1 this is 1.5 volts, for sensor 2 this is 0,75 volts and for sensor 3 this is 2.3 volts. This implies that there is no consistent absolute accuracy for the sensors. This implies that the sensors will have to be individually calibrated for each application. See figure 4.7, page 34, of Appendix C.

4. In all the results the sensor readings reached a minimum voltage after a minute or two, after which the readings slowly increased. Unfortunately it can not be ascertained from this experiment, whether this is part of the sensor response, or if the actual hydrogen concentration decreases.

4.5 Experiment 4

See Chapter 5, page 37, of Appendix C for more information.

4.5.1 Purpose

Laboratory tests on the performance of the commercial hydrogen monitor.

4.5.2 Method

The commercial hydrogen monitor was bolted to the gas-tight chamber. Various amounts of hydrogen gas was injected into the chamber. For first tests, no oil was present in the container. In the final tests the chamber was filled with oil. Air bubbles also were introduced into the chamber, the response of the commercial hydrogen monitor noted.
The commercial hydrogen monitor's response to temperature change also was noted.

4.5.3 Results and conclusions

1. The commercial hydrogen monitor's repeatibility is good, but the absolute accuracy was poor, overread by approximately 100%. This implies that either this particular commercial hydrogen monitor is inaccurate and requires proper laboratory calibration, or the Ostwald coefficient value used is wrong. See figure 5.2, page 42, of Appendix C.

2. The commercial hydrogen monitor is very temperature sensitive.

3. The commercial hydrogen monitor reading is sensitive to the presence of air bubbles.

4.6 Experiment 5

See Chapter 6, page 44, of Appendix C for more information.

4.6.1 Purpose

Calibration of the fuel cell hydrogen and resistive element hydrogen sensor using the gas-tight chamber.

4.6.2 Method

The 3 resistive element hydrogen sensors were sealed in the gas-tight chamber. The fuel cell hydrogen sensor was bolted to a port on the chamber. Various quantities of hydrogen gas were injected into the chamber. The outputs from the sensors were recorded with the datalogger.

4.6.3 Results and conclusions

1. The resistive element hydrogen sensors will have be individually calibrated. The results for the resistive element hydrogen sensors are similar to experiment 3. See figure 6.2, page 50, of Appendix C.

2. The repaired fuel cell hydrogen sensor was inaccurate. See figure 6.4, page 52, of Appendix C.

4.7 Experiment 6

See Chapter 7, page 53, of Appendix C for more information.

4.7.1 Purpose

Dissolved hydrogen gas concentration in the oil at the various ports.

4.7.2 Method

Hydrogen gas was injected into the bottom port using a gas-tight syringe. The hydrogen gas concentration was monitored in the air space above the oil using the fuel cell hydrogen sensor. The experiment was left for 24 hours so that the hydrogen gas could dissolve through the oil. Two oil samples were taken from the same port using the gas-tight syringes.

4.7.3 Results and conclusions

1. From all the tests, the acetylene concentration was approximately the same. This indicated consistency in the gas-in-oil analysis.

2. The results indicate that dissolved hydrogen gas was not reaching the end of the ports.

3. When pipes were used that allowed the oil in the middle of the tank to be sampled, no conclusive results could be drawn about the effect of the height on the sampling results.

4.8 Field trials of the commercial hydrogen monitor

The commercial hydrogen monitor has been used by ESKOM on gassing transformers to monitor the hydrogen concentration levels. See figure 4.1 for the commercial monitor readings versus time. The readings have been averaged out. The graph shows a period of 4.5 days. Note how the readings drop at 00:20 hours, midnight, and reach a peak at approximately 12:00 hours, midday. The graph clearly shows that the commercial hydrogen monitor is showing a maximum reading when the ambient temperature is the highest, and a minimum reading when the temperature is the lowest.

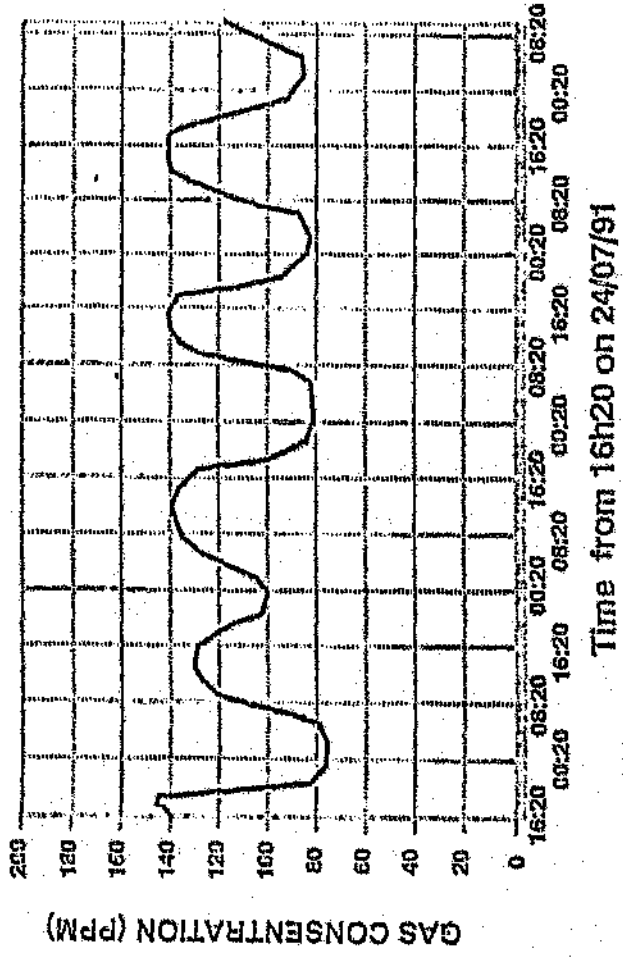


Figure 4.1 Average commercial hydrogen monitor readings versus time

5 CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations are divided into two parts : those conclusions pertaining to the feasibility of manufacturing a low cost hydrogen on-line monitor, and those conclusions that deal with the validity of the underlying principle of operation.

5.1 Low cost hydrogen on-line monitor

5.1.1 Hydrogen sensors

Conclusions

1. Comparing the fuel cell hydrogen sensor and the resistive element hydrogen sensor :

The fuel cell hydrogen sensor is expensive at R3000 while the resistive element hydrogen sensor is cheap at R130. The fuel cell used by the fuel cell hydrogen sensor has to be replaced at a cost of R1000.
The fuel cell has a lifetime of approximately 3 years while the resistive element hydrogen sensor is supposed to have an unlimited lifetime.
The fuel cell hydrogen sensor is supposed to be approximately 5% accurate, while the resistive element hydrogen sensor is totally inaccurate. Each resistive element hydrogen sensor will have to be individually calibrated before use, and probably yearly thereafter.
The fuel cell hydrogen sensor is stable with temperature and time, while the resistive element hydrogen sensor is totally inaccurate if the equilibrium temperature is not reached.
The fuel cell hydrogen sensor has a built in 4 - 20 mA loop, and therefore requires no signal conditioning electronics. The resistive element hydrogen sensors require signal conditioning electronics for converting the output of the cell to a 4 - 20 mA loop. The electronics will cost approximately R200.

2. Both sensors are therefore not suitable for a low cost hydrogen monitor (<R5000). The initial price of the fuel cell hydrogen sensor is high, and requires expensive fuel cell replacements every 3 years. The resistive element hydrogen senso. :equires laboratory calibration approximately every year.
The cost in man-hours could be prohibitive if the monitor is far in the field. Assuming that the monitor requires 2 hours for removing from the transformer, 2 hours for laboratory calibration, and 2 hours for installing, the cost would be approximately 6 x R50 = R300 + Cour..er service from the local region to E.I and back. Note that this cost could easily exceed the cost of replacing the fuel cell hydrogen sensor sensor, if the fuel cell hydrogen sensor is used.

3. If the cost of the on-line monitor is less of a consideration, the fuel cell hydrogen sensor is the best choice. The resistive element hydrogen sensor is not suitable for accurate measurements, and will only be suitable for a go / no-go type of monitor. Unfortunately this type of monitor is not suitable for reliable on-line monitoring. A monitor must rather give an alarm for an user selectable increase in the hydrogen concentration over a certain time. Depending on the design of the monitor, using the fuel cell hydrogen sensor has the potential of requiring no calibration prior and during use on the transformer. This implies that local manufacture of the instrument is feasible.

Recommendations

1. A number of fuel cell hydrogen sensors should be obtained, and evaluated for accuracy and repeatibilty.

2. If the fuel cell hydrogen sensor conforms to the manufacturer's specifications, it should be used for future designs rather than the resistive element hydrogen sensor.

5.1.2 Membrane separation of the dissolved hydrogen gas from the oil

Conclusions

1. Using a membrane to separate the dissolved hydrogen gas from the oil has a number of disadvantages. There are two methods of using the membrane. The one method is to allow the hydrogen gas dissolved in the oil to reach equilibrium with the hydrogen gas in the gas chamber on the other side of the membrane. This was the method used in the hydrogen monitor designed by Hitachi. The problem with this method is that the time taken to reach equilibrium is inordinately long - 72 hours in the case of the Hitachi on-line monitor.
The other method is to use the membrane in such a way that the hydrogen gas that diffuses through the membrane is less than the hydrogen gas used up by the sensor. This is the method used by the commercial hydrogen monitor. This implies that the sensor reading is proportional to the rate of diffusion, which in turn is proportional to the quantity of dissolved hydrogen.
This method is very temperature sensitive, because the rate of diffusion has an exponential rise for a temperature rise.

2. It is very difficult to obtain suitable membranes in S.A. Eventually the membrane used in the designed on-line monitor was specially manufactured by Engineering Investigations Applied Chemistry department. Unfortunately the consistency between the different membranes made cannot be guaranteed. The final on-line monitor will still require a standard commercial membrane for easy manufacture.

3. The membrane has to be in contact with moving oil. The experimental results clearly show that no reliable results can be obtained from the on-line monitor if the monitor is bolted to a port a small distance from the oil body.

Recommendations

1. Alternative methods for separating the dissolved hydrogen gas from the oil should be used for future on-line monitor designs.

2. This method must also be able to sample the oil deep in the transformer for accurate on-line monitoring.

5.2 Hydrogen on-line monitoring

5.2.1 Monitoring the hydrogen concentration in the air space of a transformer

Conclusions

1. This would be the ideal way of on-line monitoring of current transformers. All the experiments performed showed fast and consistent increases in the hydrogen concentration in the air space of the experimental tank. This method would be also cheap, because no apparatus is required for removing the dissolved hydrogen gas from the oil. Unfortunately this method cannot be implemented due to safety considerations. No modifications can be made to the high voltage side of the current transformers. Also no leads can be taken from the high voltage side to ground level. The only way that this method can be implemented, is if the hydrogen monitor is designed into the current transformers at manufacture.

2. This method could be implemented on high voltage transformers. While not possessing the problems associated with current transformers, more research will have be conducted. If this does work, this would be a very cheap method of monitoring high voltage transformers.

Recommendations

1. Tests should be conducted on the high voltage transformers to ascertain whether this method is suitable for on-line monitoring. This will require an accurate on-line monitor to compare the hydrogen concentration in the oil to the hydrogen concentration in the air space.

5.2.2 Oil sampling techniques

Conclusions

1. Large problems were encountered in taking reliable oil samples for hydrogen gas concentration. Acetylene, and to a lesser degree the other hydrocarbon gases, are not very sensitive to the sampling method.

2. The gas-tight syringes proved reliable for oil sampling. Unfortunately their cost , approximately R550, rules out the possibility of using the syringes for general oil sampling. The tin sample vessels used are probably still the most cost effective method for general sampling. But the hydrogen gas level should not be used to assess the condition of the transformer. Acetylene is the best gas to check for, but will not indicate increases in partial discharge and other low level faults.

3. If any oil samples are taken, it is most important that there are no air bubbles in the oil. This applies equally to using the gas-tight syringes as to using the standard sample tins. The hydrocarbon gases dissolved in the oil, to varying degrees diffuses into any air bubbles in the oil. For example, most of the acetylene will stay in the oil, while most of the hydrogen gas will diffuse into the air bubbles.

Recommendations

1. An experiment should be set up to quantify the errors due to using the standard sample vessels for the various gases.

2. This must be repeated using the gas-tight syringes to quantify the error in using the syringes. If the results are positive, the syringes could be used possibly used for strategic transformers suspected of partial discharge activity.

3. No air bubbles must be present in the sample vessels.

5.2.3 Commercial hydrogen monitor

Conclusions

1. The particular commercial hydrogen monitor that was tested was inaccurate, despite electronic calibration prior to the experiments.

2. The commercial hydrogen monitor is very temperature sensitive. This was confirmed by the commercial hydrogen monitor reading on an actual transformer in the field.

3. The commercial hydrogen monitor is sensitive to any air bubbles in the oil in contact with the membrane.

4. The commercial hydrogen monitor must be in contact with the main oil body or in the stream of the oil flow for reliable measurements. The manufacturers recommendations on this must be followed.

5. The cost of the commercial hydrogen monitor precludes wide usage on current transformers.

Recommendations

1. A number of commercial hydrogen monitors should be tested for accuracy using an accurate mixture of hydrogen gas and oil.

2. If this monitor is used on power transformers, the results must take into account temperature variations to prevent false alarms.

5.2.4 Effect of the position at which the monitor is bolted on the transformer

Conclusions

1. The results indicate that no dissolved hydrogen gas reaches the ends of the ports.

Recommendations

1. The on-line monitor must not be bolted on to a transformer via a port. It should be in direct contact with the main body of the oil.

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APPENDIX A

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1 INTRODUCTION

This appendix consists of the literature survey which ascertains the current state-of-the-art in gas-in-oil analysis and on-line monitors.

This appendix has been written as a self-contained document, therefore an index and bibliography is included.

This document should prove invaluable to somebody who requires a comprehensive summary of GIO analysis techniques for transformers and on-line monitoring techniques.

The appendix is divided into the following sections :

Chapter 2 provides some background information on why gas-in-oil analysis is currently the proven method for assessing the condition of the insulation in transformers.

Because the MSc(ENG) is directed strongly towards a gas-in-oil on-line monitor, extensive information is provided in Chapter 3 on gas-in-oil analysis. This includes the theoretical background, the actual method of using it, and the various methods of interpreting the results.

Chapter 4 provides information on High Performance Liquid Chromatography which promises to be very important in the future for diagnosing insulation deterioration.

Chapter 5 provides a summary of some of the current approaches to on-line gas-in-oil monitors.

2 BACKGROUND INFORMATION ON CONDITION MONITORING OF TRANSFORMERS

The first commercial transformers for the transmission of electricity, Stanley transformers, were air-cooled. Soon after their introduction, George Westinghouse (founder of the Westinghouse Company) immersed the entire transformer in a tank of oil and spaced the laminations in the core so that the oil could circulate by convection among them. The oil contributes to the dielectric strength of the transformer, provides efficient cooling, protects transformer core and coil assembly from chemical attack, and prevents buildup of sludge.[1]
Over the years, progressively more stress has been placed on successively less oil for comparable transformer ratings. See table 2.1. [2]

Table 2.1 Typical oil content according to the transformer design period

Design period	Litres of oil per KVA of transformer
1915	7.6
1930	3.8
1945	1.9
1960	1.3
1977	0.5

Insulation is the weakest link in a transformer and the oil is an integral part of the insulation system. Therefore the condition of the insulation can be checked by analysing the oil. The most common methods of checking the oil are - testing the general condition of the oil, analysing the oil for dissolved hydrocarbon gases, and analysing the oil for heavier suspended hydrocarbon components.

The American Society for Testing and Materials (ASTM) lists 30 tests in publication D117 of which the most important are listed in table 2.2. [2]

Table 2.2 Eight most important ASTM tests for in service transformer oil

ASTM test	Information provided by test
Dielectric breakdown strength	Free water in oil
Neutralization number	Acid in oil
Interfacial tension	Sludge in oil
Colour	Marked change indicates problem
Specific gravity	Check for contaminants
Opacity	Cloudiness implies contamination Sediment indicates deterioration
Power factor	Indicates presence of oxidation or contamination

Unfortunately none of the tests give direct indication of the insulation deterioration. In contrast gas-in-oil analysis using gas chromatography (GS) has been established as the most reliable method of indicating internal transformer faults and insulation breakdown. Also recently, liquid chromatography has been used to isolate heavier hydrocarbon compounds that indicate insulation breakdown.

Chromatography can be traced back to the turn of the century, when a Russian botanist, M. S. Tsevet, separated a mixture of plant pigment prior to identification of the compounds.
Chromatography was advanced in the 1950's to where it was possible to effect the separation of gases. In the 1960's GC was applied to identifying fault gases dissolved in transformer oil. Table 2.3 indicates the most common gases identified in oil. [3]

Table 2.3 Gases in oil usually tested for in oil

Hydrogen	H_2	*
Oxygen	O_2	
Nitrogen	N_2	
Methane	CH_4	*
Carbon Monoxide	CO	*
Ethane	C_2H_6	*
Carbon Dioxide	CO_2	
Ethylene	C_2H_4	*
Acetylene	C_2H_2	*

(* denotes combustible gases)

Various empirical methods have been proposed to identify the type of fault and its severity.
These include checking for limits (in parts per million range) of certain key gases (hydrogen, acetylene etc), checking the total combustible gas present, and the Rogers and Dorenburg methods which use ratios of various gases to indicate the type of fault.

Recently some transformers have failed due to slight overheating of paper at 110 - 120 degrees Centigrade. Gas analysis cannot differentiate between that and general oxidation of oil. High Performance Liquid Chromatography (HPLC) has been used to separate hydrocarbon compounds produced exclusively by thermal degradation of paper at temperatures from as low as 110 degrees Centigrade. The presence of furfuraldehyde has shown positive correlation to increases in paper insulation overheating.
High Performance Liquid Chromatography analysis lacks the sensitivity of Gas-in-Oil analysis.

Also building a simple and cost-effective on-line monitor based on HPLC techniques will be impossible with the present state of art. It remains a sophisticated laboratory technique. [4]

Other methods of insulation condition monitoring have been proposed. These include direct partial discharge measurement and acoustical analysis.

The breakdown of high voltage solid insulation in service by electric treeing or tracking is preceded by a period of emission of partial discharge pulses. There are a number of standard laboratory methods for measuring partial discharge activities in transformers. In the past nearly all such diagnostic testing required costly temporary removal of the equipment from service. Partial discharge testing done during normal operation was considered impossible due to the interference from the much greater electrical noise signals caused by the power line carrier, radio stations, transmission line corona, breaker operations, etc. Also, for some insulation systems, the time between the onset of detectable partial discharge and catastrophic failure could be too short for the condition to be detected by a practical economic periodic test procedures.[5][26]
A Fault Anticipator for Substation Equipment (FASE) system has been developed that can detect and identify a partial discharge in a noisy substation environment. Ferrite cores, which are sensitive to partial discharge pulses, are placed around the ground leads of the current transformers . The outputs are connected to a common controller which records the partial discharge pulses and their direction. Noise pulses on the system bus will be picked up at all the current transformers and thus rejected. However if one current transformer consistently produces a pulse of opposite polarity to that from all the current transformers, it is identified as being in trouble. Unfortunately this technique is only suitable for current transformers connected to a common bus. The time interval between partial discharge onset and failure may vary from a few minutes to thousands of hours, depending on the local stress enhancement, and the nature of the insulating system.[26]

Also more importantly, there is no direct relationship between the rising partial discharge activity and insulation deterioration. The experiments performed at the CSIR indicate that while the hydrogen level in a current transformer continued to rise due to a fault, the partial discharge activity remained relatively constant. [6]

Recently research has been done on using acoustical emission analysis for detection of ageing in transformers.

The ageing of electrical insulation material is connected with structural degradation and molecular changes. The energy content varies and besides quantum emission, also phonon excitation and propagation occurs. Partial discharges will result in acoustical emission. Depending on the amount of disengaged energy a sound detection is possible. An acoustical analyser has been built that can automatically distinguish between hot spots in solid and liquid insulation, partial discharges, mechanical crack initiation and propagation. But further investigations have to be carried out in order to find solutions for analysing superpositions of two or more sources with different intensities.[7] Because this technique is still in its infancy, its usefulness for on-line monitoring is still limited.

The power factor of electrical insulation has been recognized as a good indicator of its quality and future serviceability. Almost any form of degradation of the insulation will, sooner or later, increase its power factor. A common practice in the industry has been to periodically take the equipment out of service, and measure its power factor and capacitance. Recently a microcomputer based apparatus has been developed which monitors power factor and capacitance continuously, with the transformer on-line. Initial tests done on current transformers indicate that it provides an indication of a possible incipient fault. Abundant evidence indicates that an increasing power factor is indicative of degrading insulation.

The first limiting factor with this method is that the apparatus only works on transformers with a capacitance tap.[28] Secondly, power fac..r measurement is a bulk phenomenon. Power factor change due to localized discharges could be obscured by the overall measurement. This is supported by the work done by Reynders and Meal. While a rising hydrogen concentration indicated a fault in a current transformer, the power factor remained relatively constant, though it was high. [6]

3 GIO ANALYSIS

A complete discussion of all the aspects of Gas-in-Oil (GIO) Analysis is given in this chapter. This is divided into the following sections :

The theoretical basis for GIO analysis - a theoretical prediction for gases produced due to various faults based on thermodynamic principles is presented.
Gas chromatography - a brief description on how gas chromatography works.

Extraction of oil - general procedures for removing oil from the transformers.

Interpreting the GIO results - various methods for interpreting the results, these include Roger's ratio test, Laborelec method, etc.

Conclusion - The general conclusions that can be drawn from the literature survey on what should be the best approach to an on-line monitor to detect incipient faults in transformers.

3.1 Theoretical basis for GIO analysis

Different types of faults - arcs, hot spots, partial discharges, etc - can be defined in terms of localized temperatures which they generate. Halstead [8] proposed a model which correlated equilibrium pressures of the basic hydrocarbon gases produced in a transformer to a particular temperature. These equilibrium pressures are proportional to the concentrations of the various hydrocarbon gases produced.

For the complete range of temperature faults, the transformer oil will decompose to their constituent molecules, slowly for low temperature faults (overheating) and rapidly for high temperature faults (arcing). Since the end products (hydrocarbon gases

and carbon) and the original reactants (transformer oil) are the same, the overall free energy for the following process will be fixed :

oil molecules into :

C_2H_2, C_2H_4, CH_4, C_2H_6, H_2

The model system will thus be taken as being one in which all the molecules involved are totally decomposed to products given in (1), with each product being in equilibrium with all the others and the overall pressure of the system being taken as 10^5 Nm^{-2} (1atm).
The equilibrium partial pressure of various gaseous reaction products were calculated using the equilibrium constants for the following reactions, at temperatures between 500K and 2000K.

$C\ (solid) + 2H_2\ (gas) = CH_4\ (gas)$

$2CH_4\ (gas) = C_2H_4\ (gas) + 2H_2\ (gas)$

$C_2H_4\ (gas) = C_2H_2\ (gas) + H_2\ (gas)$

$C_2H_4\ (gas) + H_2\ (gas) = C_2H_6\ (gas)$

$C_2H_2\ (gas) + 2H_2\ (gas) = C_2H_6\ (gas)$

The results are shown in figure 3.1. [8]

These equilibrium partial pressures are proportional to the concentration of the gas in oil. Various ratios of the hydrocarbon gases were compared to actual experimental results and were found to correspond. See table 3.1 for a list of calculated gas ratios and table 3.2 for actual experimental results.

Table 3.1 Calculated gas ratios

Fault temperature (Degrees Kelvin)	Ratio $\frac{C_2H_2}{CH_4}$	Ratio $\frac{C_2H_4}{C_2H_2}$	Ratio $\frac{CH_4}{H_2}$
500	$4X10^{-23}$	$3X10^{10}$	50^{1}
1000	$2X10^{-8}$	400	9
1500	$3X10^{-3}$	0.3	$5X10^{-3}$
2000	1.3	10^{-2}	10^{-3}

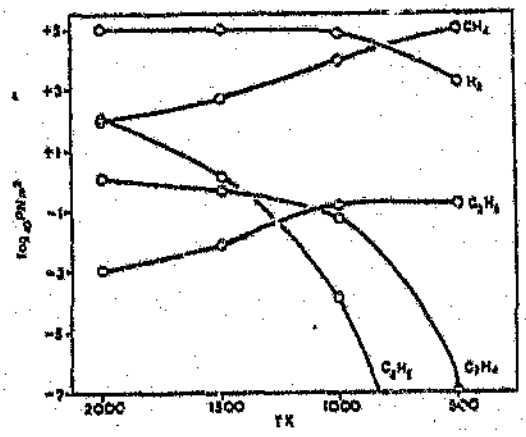


Figure 3.1 Equilibrium pressures system with total system pressure equal to 1 atmosphere

Table 3.2 Experimental gas ratio results

Fault temperature (Degrees Kelvin)	Ratios C_2H_2 / CH_4	C_2H_4 / C_2H_2	CH_4 / H_2
593 (Hot spot)	0	infinite	1.3
628 (Hot spot)	2X10	8	2.1
about 2000 (Arcing)	4	0.1	0.1

Therefore the various methods used to analyse GIO analysis results can be related to theoretical predictions.

3.2 Degassing oil

Dissolved gases are extracted from a sample of oil by expansion of the oil sample in a pre-evacuated known volume. The vacuum expanded gases are compressed to atmospheric pressure and the total volume measured. The degassification apparatus is evacuated to a 10^{-3} absolute pressure of about 10 Torr or less by means of a vacuum pump. The degassing flask is gently heated (up to 100 degrees Centigrade) and the oil continuously stirred with the help of a magnetic stirrer. This takes about 10 minutes after which the gases are drawn out and transferred to the Gas Chromatograph. From this method 99 percent of the dissolved gases in the oil can be extracted. [9][10]

3.3 Gas Chromatography

Gas Chromatography (GC) is a process of separation, identification and quantification of volatile

mixtures. In GC the component gases to be separated are carried through the separation column by an inert gas (carrier gas). The separation column consists of a non-volatile solvent (Silica gel, Porapak Q, Molecular Sieve 5A, activated charcoal etc) supported on an inert size graded solid (Solid support). The solvent selectively retards the sample components according to their distribution coefficient, until they form separate bands in the carrier gas. These component bands leave the column in the gas stream and are recorded as a function of time by a detector. Generally the components are separated into three different runs

I - Analysis of hydrocarbons methane, ethane, ethylene, acetylene, propane and propylene with the flame ionisation detector.

II - Analysis of hydrogen with the katharometer detector.

III - Analysis of carbon monoxide and carbon dioxide with the flame ionisation detector and a catalyst. [9][10]

3.4 Extraction of oil

As an example and guide the following method used by CEGB is summarised below.[25]

The field use of dissolved gas-in-oil analysis requires a simple robust method which requires little skill. Previously the sampling valves fitted to transformers were used. These proved unsuitable for providing reliable samples because they readily permitted the ingress of moisture and air into the sample. CEGB developed a new valve for use on new transformers or for fitting to the drain valves of older transformers.

As a temporary method, though, the samples are drawn from a drain or filling line which is temporarily stoppered by a neoprene bung bored to take a small

bore (1/4") nylon tube. Samples are taken in 500ml glass bottles which are filled with the upward displacement of air. They are sealed with plastic screw caps containing flanged conical polythene inserts after leaving a small bubble above to allow for expansion.
Samples taken in this way have been shown to be reproducible and stable for up to 6 months. [25]

3.5 Interpreting the results

There are various methods for interpreting the results of GIO analysis. A short description of the following methods are given :

- Setting allowable limits for the amount and the rate of production of various hydrocarbon gases.
- Setting a limit for the amount and rate of production of the Total Combustible Gases (TCG).
- Checking for key hydrocarbon gases.
- Ratio tests which include both Roger's test and Dorenburg's test.
- Gas patterns.

3.5.1 Allowable limits for the gases

Various lists of the proposed allowable and non-allowable limits for certain gases have been proposed. These are based on results from a number of in-service transformers, and noting what constitutes a normal trend in transformer deterioration and what does not.

For Czechoslovakia the following limits have been proposed [11] :

Gas	Upper Limit (ppm)
CO_2	3000-6000
CH_4	100
C_2H_2	0
C_2H_6	10

Dorenburg has the following limits for his ratio test to check if the analysis is valid [12] :

Gas	Upper Limit (ppm)
H_2	200
CH_4	50
CO	1000
C_2H_2	15
C_2H_4	60
C_2H_6	15

These norms were refined and then incorpor ed into the ANSI/IEEE Guide as 90% probability norms ;] :

Gas	Upper Limit (ppm)	
	Generating Transformers	Transmission Transformers
H_2	240	100
CH_4	160	120
C_2H_2	11	35
C_2H_4	190	30
C_2H_6	115	65

The CSUS Guidelines give both an upper limit for normal operation and a lower limit for abnormal operation with a region in between for which both normal or abnormal operation is not clearly defined [13] :

Gas	Upper Limit for Normal Operation	Lower Limit for Abnormal Operation
H_2	150	1000
CH_4	25	80
C_2H_2	15	70
C_2H_4	20	100
C_2H_6	10	35
CO	500	1000
CO_2	10 000	15 000
N_2	10 000 - 100 000	-
O_2	2 000 - 3 500	-

From statistical analyses done on transformers in Finland the following limits have been proposed for healthy transformers [27, :

Gas	Upper Limit (ppm)
H_2	100
CH_4	100
C_2H_2	30
C_2H_4	100
C_2H_6	150
CO	500

The Society of Electrical Cooperative Research of Japan proposed the following caution levels [14] :

Transformer Rating	Upper limit for normal operation				
	H_2	CH_4	C_2H_4	C_2H	CO
275kV, > 10MVA	400	200	300	150	300
275kV, < 10MVA	400	150	200	150	300
500kV	300	100	100	50	200

3.5.2 Total Combustible Gases (TCG)

TCG detection was readily accepted in nitrogen gas preservation systems where Buchholz type relays are not used. The gases were vacuum extracted from the oil. This was adapted by U. S. Manufacturers for conservator designs. The amount of combustible gases (see Chapter 3, page 4 and 5 for what gases are combustible) are measured by the heat produced, usually employing a thermal conductivity cell. [12]

IEEE C57.104 recommends the procedure in figure 3.2. [12]

CSUS guidelines recommend the following [13] :

TCG Lower Limit for Normal Operation	TCG Upper Limit for Abnormal Operation
300ppm	5000ppm

ASEA proposes the following guidelines based on statistics from European countries [15] :

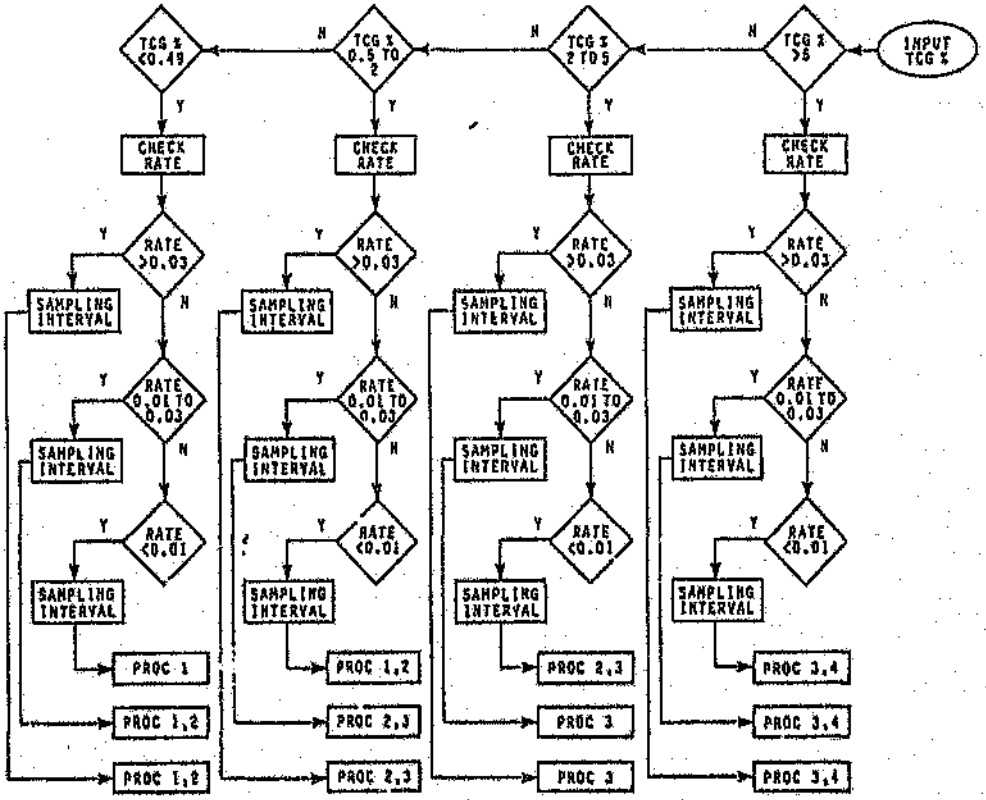
Open transformers : okay if TCG production <= 1 ppm per day

Sealed transformers : okay if TCG production <= 2 ppm per day

The Society of Electrical Cooperative Research of Japan proposed the following caution levels for total TCG and TCG generation per year[14] :

Transformer Rating	Upper TCG limit(ppm)	Upper TCG generation per year (ppm/year)
275kV, > 10MVA	1000	350
275kV, < 10MVA	700	250
500kV	400	150

In conclusion, continuous TCG in Nitrogen gas preservation systems units has the potential for the fastest response to all kinds of faults - from slow to rapidly developing. [12]



Key to sampling interval and procedure

TCG Level	TCG Rate (% TCG/Day)	Sampling Interval* Rate: Decrease	Sampling Interval* Rate: Constant	Sampling Interval* Rate: Increase	Recommended Operating Procedure** Rate: Decrease	Recommended Operating Procedure** Rate: Constant	Recommended Operating Procedure** Rate: Increase
> = 5%	= >0.03	F	F	F	3	4	4
	= >.01; <.03	D	E	F	3	4	4
	= <0.01	C	D	E	3	3	4
<5; = >2%	= >0.03	E	F	F	3	3	4
	= >0.01; <.03	C	D	E	3	3	4
	= <0.01	B	C	D	2	3	3
<2; = >.5%	= >0.03	D	E	F	3	3	4
	= >0.01; <.03	B	C	D	2	3	3
	= <0.01	A	B	C	1	2	3
<0.5%	= >0.03	C	D	E	3	3	4
	= >0.01; <.03	A	B	C	1	2	3
	= <0.01	A	A	B	1	1	2

*A = 1—6 months; B = monthly; C = weekly; D = 30 days; E = daily; F = immediately.

**1 = Continue normal surveillance.
2 = Advise manufacturer; caution; determine load dependence; analyze gas space and oil for components.
3 = Advise manufacturer; extreme caution; reduce load and plan outage; F rate constant; check acoustic emission; analyze gas space and oil for components.
4 = Advise manufacturer; hazardous to continue operation; reduce or drop load if possible, plan for outage as soon as possible.

Figure 3.2 TCG procedure based on IEEE C57.104

3.5.3 Key Gases

Different faults result in different "key gases". The following is a list of the different types of faults that occur in transformers with a list of key gases. Alternative sources are given since they do not all agree on the same key gas for a particular fault.

Thermal decomposition of oil :

- H_2 [16]
- H_2 [11]
- light hydrocarbons [3]
- C_2H_4 [17]

Thermal decomposition of oil to destruction :

- light hydrocarbons + H_2 [3]

Thermal decomposition of cellulose (insulation) :

- CO + CO_2 [11]
- CO + CO_2 [3]
- CO [17]

Thermal decomposition of cellulose to destruction (pyrolysis) :

- CO_2 + H_2O + carbonaceous materials [17]

Thermal decomposition of oil and insulation :

- H_2 [16]
- $CO + CO_2$ [11]
- C_2H_4 [18]

Weak discharge (corona) :

- H_2 [16]
- H_2 [11]
- H_2 [18]
- H_2 [3]

Heavy discharge (arcing) :

- C_2H_2 [16]
- C_2H_2 [11]
- C_2H_2 [18]
- C_2H_2 [17]

The IEEE presents a generic method : See table 3.3. [13]

There is agreement among the different sources about key gases. This is especially true of weak and strong discharges.

Table 3.3 IEEE generic method

Detected gases with the corresponding interpretations.

(a) Nitrogen plus 5 percent or less oxygen :
Normal operation of transformer.

(b) Nitrogen plus more than 5 percent oxygen :
Check for tightness of sealed transformer.

(c) Nitrogen, carbon dioxide and/or carbon monoxide :
Transformer overloaded or operating hot, causing some cellulose breakdown. Check operating conditions.

(d) Nitrogen and hydrogen :
Corona discharge, electrolysis of water, or rusting.

(e) Nitrogen, hydrogen, carbon dioxide, and carbon monoxide :
Corona discharge involving cellulose or severe overloading of transformer.

(f) Nitrogen, hydrogen, methane with small amounts of ethane, and ethylene :
Sparking or other minor fault causing some breakdown of oil.

(g) Nitrogen, hydrogen, methane with carbon dioxide, carbon monoxide, and small amounts of other hydrocarbons; acetylene is usually not present :
Sparking or other minor fault in presence of cellulose.

(h) Nitrogen with high hydrogen and other hydrocarbons including acetylene :
High energy arc causing rapid deterioration of oil.

(i) Nitrogen with high hydrogen, methane, high ethylene, and some acetylene :
High temperature arcing of oil but in a confined area, poor connections or turn-to-turn shorts.

(j) Same as (i), except carbon dioxide and carbon monoxide present :
same as (i), except arcing in combination with cellulose.

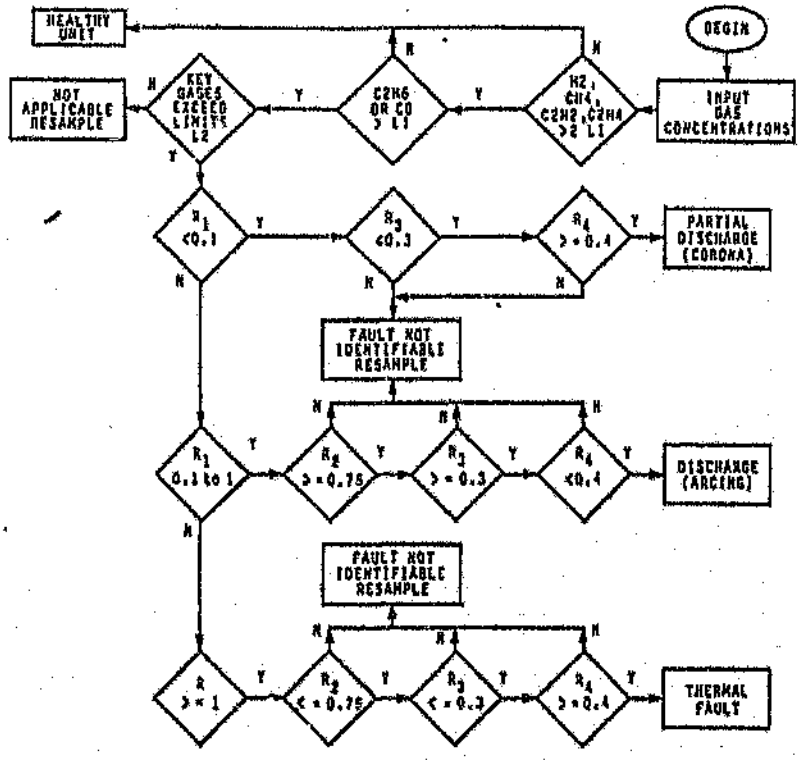
3.5.4 Ratio methods

Using ratios of various hydrocarbon gases can isolate the fault. Also using concentration ratios is less dependent on measuring precision.
Two people, E. Dorenburg and R. Rogers, were primarily responsible for developing the ratio methods. Both based their work on Halstead's theory (See Chapter 3.1) and also statistical analysis of case histories.

Figura 3.3 describes Dorenburg's fault identification procedure [12].

Roger's method was modified and incorporated in the EC 599. Figure 3.4 illustrates this method. [12]

Laborelec method which is used in Belgium is shown in figure 3.5 below. [24]



L1*		L2**
0.9 Prob Limits	Ratio	Key Gas Limits for Valid Ratio Analysis
CH4 = 50	$R_1 = \frac{CH4}{H2}$	CH4 >50 OR H2 >200
H2 = 200	$R_2 = \frac{C2H2}{C2H4}$	C2H2 >15 OR C2H4 >60
CO = 1000	$R_3 = \frac{C2H2}{CH4}$	C2H2 >15 OR CH4 >50
C2H2 = 15	$R_4 = \frac{C2H6}{C2H2}$	C2H2 >15 OR C2H6 >15
C2H4 = 60	"	"
C2H6 = 15	"	"

*: Limits L1 represent values including 90 percent of the sample population.

**: Dornenburg stipulates that at least one gas in each ratio must exceed the L1 limit for valid ratio analysis.

Figure 3.3 Dorenburg's identification procedure

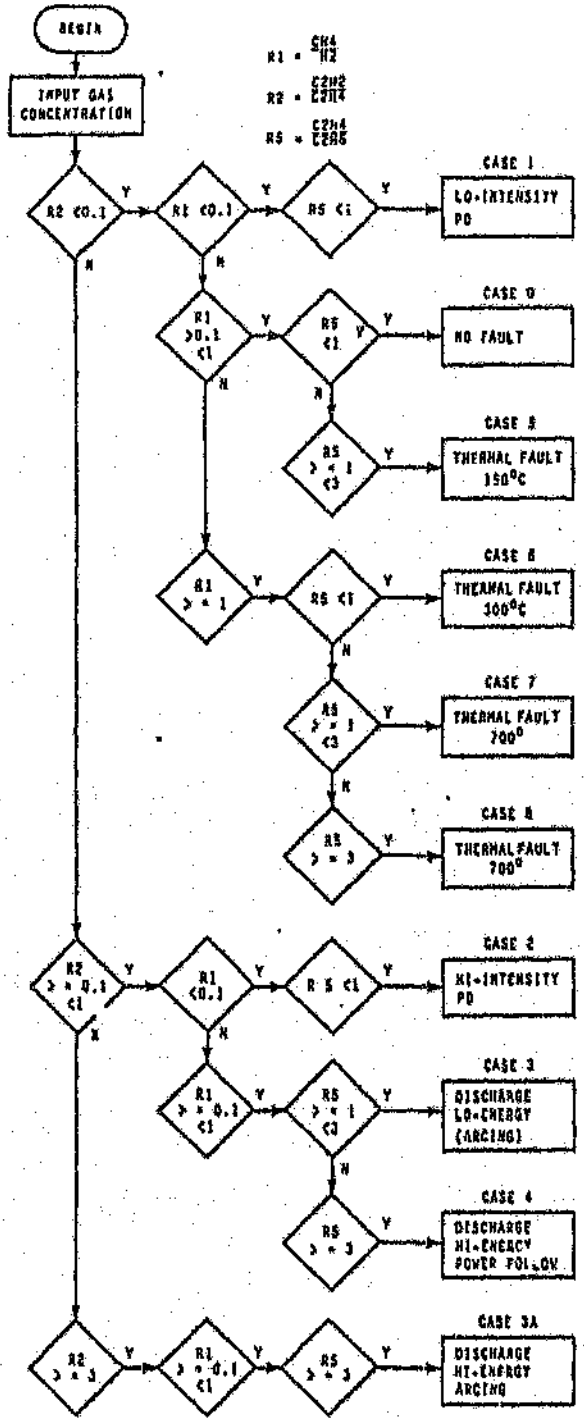


Figure 3.4 Roger's identification procedure

Dissolved gases		Service life of oil (years)							
		≤ 5		6 - 10		11 - 15		> 15	
Nature	Concentration (ul gas/l oil)	GRC	RC	GRC	RC	GRC	RC	GRC	RC
H_2	0 - 50	73	83	89	76	93	70	82	59
	51 - 100	20	10	11	13	5	11	13	18
	101 - 300	7	3		10	2	14	4	19
	301 - 1000		2		1		5	1	3
	> 1000		2						1
CO	0 - 300	67	62	63	68	51	60	56	[illegible]
	301 - 500	26	20	21	23	15	23	12	22
	501 - 1000	7	18	16	7	21	6	19	23
	> 1000				2	13	1	10	4
CO_2	0 - 1000	60	28	32	16	5	8	9	5
	1001 - 3000		44	16	44	28	24	45	37
	3001 - 9000	33	28	47	36	26	63	33	[illegible]
	9001 - 15000	7			3	28	3		
	> 15000			5	1	13	2		
CH_4	0 - 40	86	93	100	86	79	74	73	
	41 - 100	14	5		4	13	16	14	[illegible]
	101 - 300		2		7	8	7	13	
	> 300				3		3		
C_2H_4	0 - 40	100	88	79	75	72	44	73	38
	41 - 100		8	16	11	18	31	18	31
	101 - 300		2	5	8	10	19	7	27
	> 300		2		6		6	2	4
C_2H_6	0 - 40	100	100	100	88	85	87	73	74
	41 - 100				5	10	8	14	17
	101 - 300				4	5	3	11	8
	> 300				3		2	2	1
C_2H_2	0 - 10	100	91	100	66	92	26	85	28
	11 - 20		3		8	2	15	4	14
	21 - 40		2		5	2	12	4	16
	41 - 100		3		10	2	26	3	19
	101 - 300		2		10		16	1	19
	> 300				1	2	5	2	4
Number of transformers		15	61	19	146	39	140	124	388

GRC : transformers without an on-load tap changer or with a gastight tap-changer tank
RC : transformers with a non-gastight tap-changer tank

Figure 3.5 Laboralec's identification process

3.5.5 Gas patterns

This method is only generally used in Japan where it has been used for the past 15 years. A fault is diagnosed by using a gas pattern diagram, plotting concentrations of component gases with that of the most dense gas as unity. An example is given in figure 3.6. Generally three kinds of patterns, namely, H_2, C_2H_2, and CH_4 - C_2H_4 types exist. The H_2 results from an arc and partial discharges, the C_2H_2 type, from arc discharges, and the CH_4 - C_2H_4 from overheating. [29]

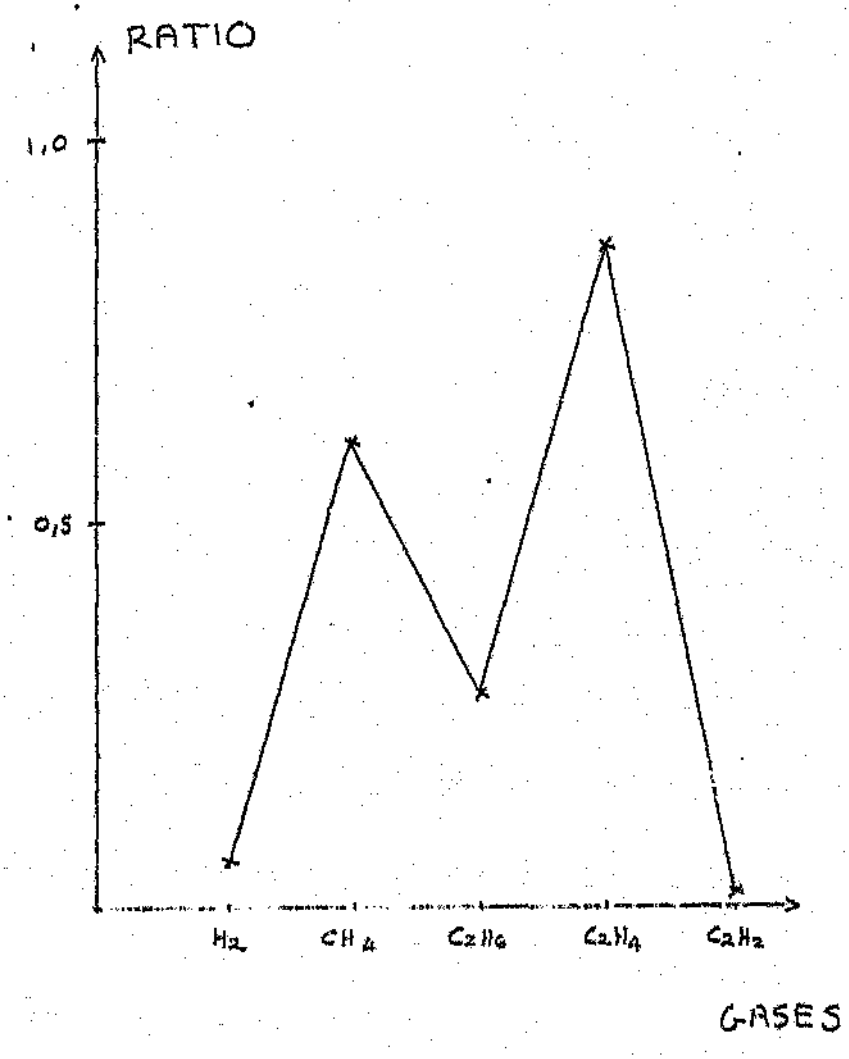


Figure 3.6 Example gas pattern

4 HPLC ANALYSIS

For the past 20 years, the general condition of oil filled electrical equipment, particularly transformers, has been monitored by determining dissolved gases in oil, using gas chromatography. A short-coming of gas-in-oil analysis is that it is non-specific. The ratios of the gases produced indicated the type of fault which may be present in the transformers, but do not give an clear indication as to the materials which may be damaged in the fault. An example is CO and CO_2 which both can be the result of the thermal decomposition of the cellulose or the long-term oxidation of the oil.

Development in the High Performance Liquid Chromatography (HPLC) has led to complementary analytical methods which allow heavier molecules dissolved in the oil to be separated and identified. These heavier liquid materials are often specific products of overheating insulation.

The most suitable liquid molecules for identification of problems are: furfuraldehyde produced by mild overheating of paper; phenol and cresols are similarly produced from synthetic resin-impregnated paper board and cumyl alcohol and alpha-methyl styrene can be detected in cables containing cross-linked polyethylene insulation.

For factory heat-run tests of transformers, using HPLC analysis for the detection of furfuraldehyde, lacks sensitivity compared to GIO analysis by about an order of magnitude. But HPLC is proving useful in detecting enhanced paper ageing in transformers, at operating temperatures well below those which produce dissolved gases such as hydrogen or methane [19].

Recently two 570MVA generator transformers operated for only 25% of their design life, due to bulging thermally degraded paper tapes that blocked off interdisc cooling ducts. This led to general

overheating at temperatures estimated to be around 110 to 120 degrees Centigrade. Normally GIO analysis will be used to detect CO and CO_2. But as mentioned before, these gases can also be in the oil as the result of oil oxidation. Also the production of other hydrocarbon gases at these temperature are very low, and therefore difficult to measure accurately.

This is where HPLC analysis is useful for detecting furfuraldehyde which, is produced from temperatures as low as 110°C [4].

Therefore for very low temperature faults where GIO analysis is not sensitive enough, HPLC analysis will be useful.

5 CURRENT APPROACHES TO ON-LINE MONITORING

The different approaches to on-line monitoring can be divided up into four main types:

- Hydrocarbon on-line monitors that check for the most common fault gases. Usually Roger's ratio test or similar, is used to predict the type and severity of the fault.
- On-line monitors that check for a particular gas dissolved in the oil to determine whether a fault exists or not.
- On-line monitors that analyse the oil for TCG which is used to check whether a fault exists or not.
- On-line monitors in addition to checking for one or more gases dissolved in oil, also check the load current, top oil temperature, hot spot temperature etc.

Examples of developed monitors that fall into the above categories will be given in the following sections.

5.1 Hydrocarbon on-line monitor

A hydrocarbon on-line monitor is basically a field counter-part to a full laboratory set-up. Various hydrocarbon gases are measured, to which Dorensburg's or Roger's ratio methods are applied. A hydrocarbon on-line monitor can be used for both on-line diagnosis, where a transformer is used to check for the existence of a fault, and on-line monitoring, where a fault is known to exist, but the type and severity of the fault is being monitored.

A short description follows of an unit developed in the United Kingdom. Figure 5.1 is a block diagram of the on-line monitor. A tubular separator is used, where oil is passed over a silicone rubber tube and air flows through the tube removing the gases which

diffuses through the tube wall. Gas samples are introduced into the chromatography column every 40 minutes by a timer. A proven commercially available flame ionisation detector (FID) is used. A typical recorder trace produced by the equipment is shown in Figure 5.2. [4]

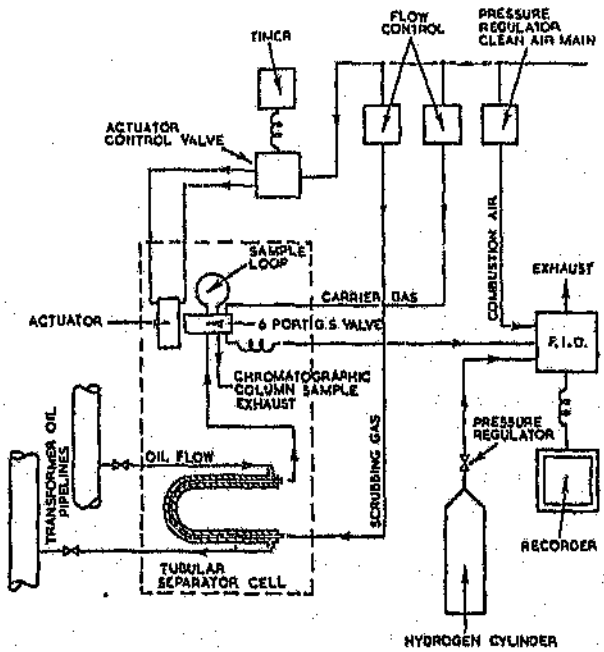


Figure 5.1 Block diagram of on-line monitor

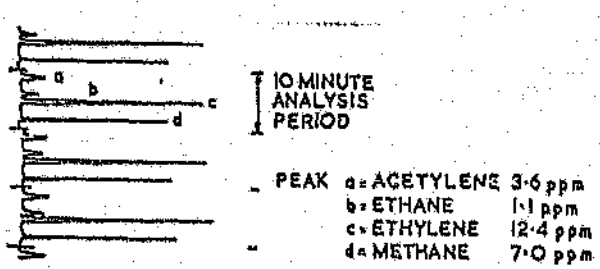


FIGURE. 4. TYPICAL RECORDER TRACE FROM A TRANSFORMER

Figure 5.2 Typical recorder trace

5.2 On-line monitor for a particular gas

On-line monitors designed to detect a particular gas are usually designed to detect H_2 gas. The reason for this lies in Halstead's theory (See Chapter 3.1). From figure 3.1.1 it can be seen that whatever the temperature of the fault is (from 200°C) hydrogen is produced and the rate of production of hydrogen increases with temperature [B4]. Note that C_2H_4 is also produced from about 200°C but the potential concentration is much lower than H_2 and therefore more difficult to detect. Two hydrogen on-line monitors based on this theory have been developed. The first was developed by H. Tsukioka and K. Sugawara from Hitachi Research Laboratory. Figure 5.3 gives an outline of the apparatus. The separation part consists of a polyimide membrane 0,005cm thick and 9,6cm in diameter, and perforated membrane protection made of a stainless steel plate 0,2cm thick, with many small holes, each about 0,2cm in diameter. This part is fixed near a flange valve on the lower part of the transformer. The gas detection part consists of a gas chamber, an electromagnetic valve and a gas sensor chamber, in which a gas sensor is installed. The gas chamber is a space in which hydrogen gas, which permeates through the membrane, is allowed to collect.
The valve opens and shuts automatically at regular time intervals in order to allow the hydrogen stored in the gas chamber to contact the gas sensor. The sensor is semiconductor based that gives an output voltage proportional to hydrogen.
Field results indicate that the instrument works well and is suitable for preventing transformer failure. The most important problem with this instrument is that the sampling period is 72 hours. A fault could easily develop in this period. [20]

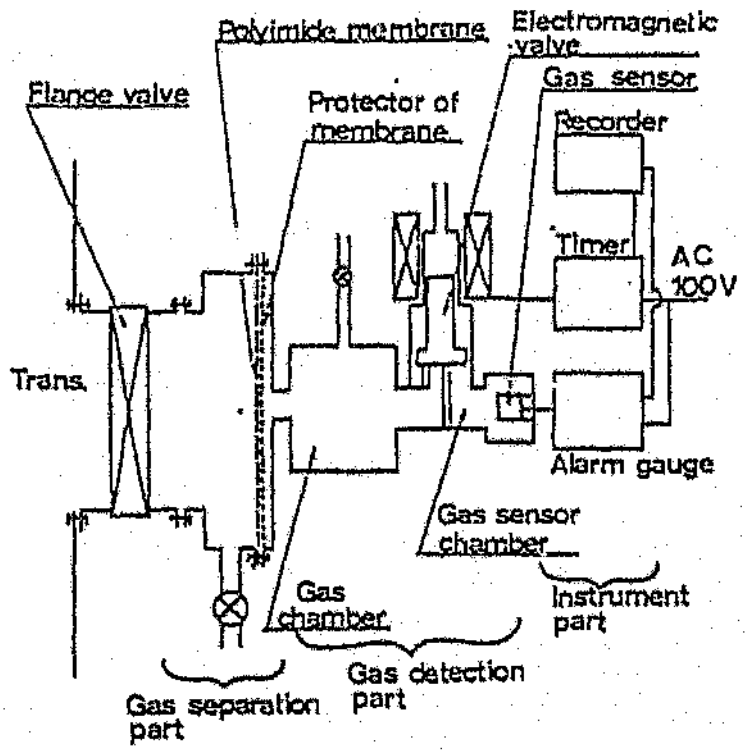


Figure 5.3 Outline of on-line hydrogen monitor

I.R.E.Q also developed a continuously monitoring device (Hydran) able to measure the level of dissolved hydrogen in dielectric oils. See figure 5.4. The Hydrogen gas dissolved in the oil diffuses through a semi-permeable Teflon membrane and is oxidised electrochemically on a platinum electrode. This electro-oxidation is coupled with the electro-production of oxygen from the ambient air on a second electrode. The electric current produced by these reactions is converted into a voltage by a load resistor, which is amplified and displayed. An alarm level can also be set.
The Hydran monitor has been in field tests where it has successfully prevented transformer failures [21].

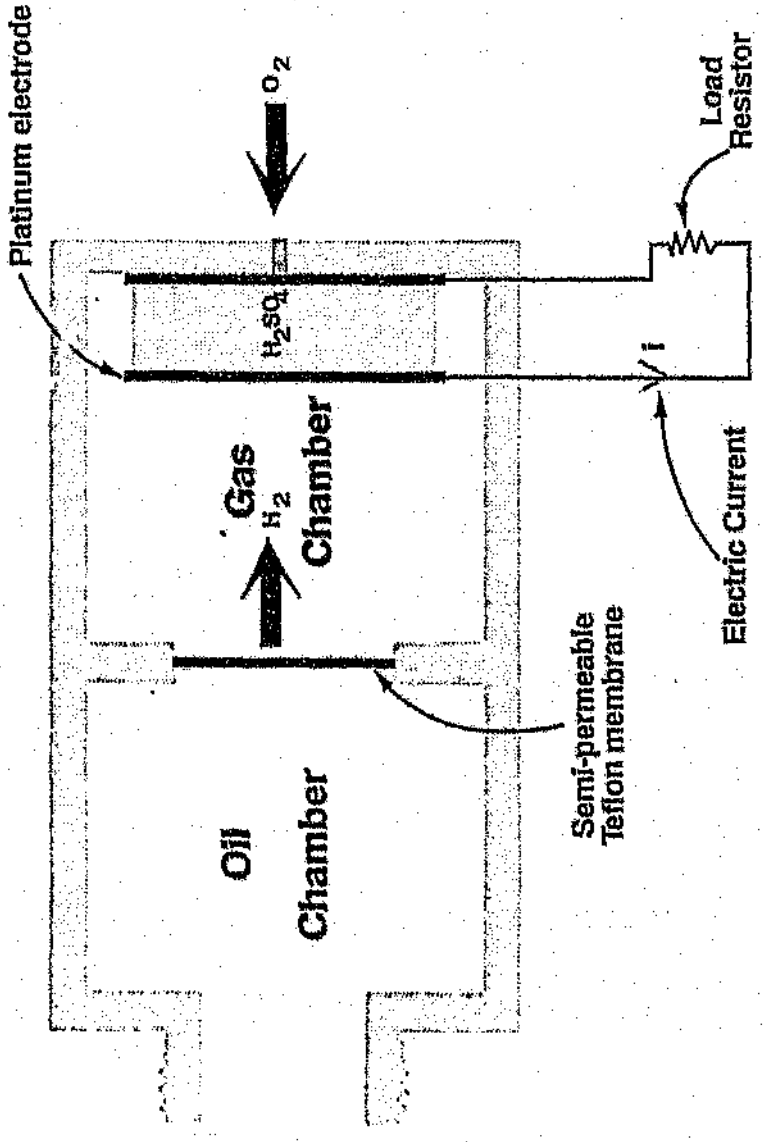


Figure 5.4 Outline of Hydran operation.

5.3 TCG on-line monitor

A TCG (Total Combustible Gas) is similar to a hydrogen gas on-line monitor in that it is used to determine whether an incipient fault will occur or not, rather than determine the type of fault.

A TCG on-line monitor was developed by Konsai Electric Power Corporation and Mitsubishi Electric Corporation. Figure 5.5 presents a block diagram of the system. The extraction unit consists of a Toricelli Bubbling extractor. Air is used as the bubbling gas. A combustion type, high sensitivity TCG detector, was specially developed for the TCG monitor. Because sensitivity of the TCG detector changes with moisture in the sample gas, the moisture is removed by freezing in a cold trap. The detector is calibrated with standard gas before every measurement. The data processing unit is composed of a chart recorder which indicates the results on chart paper. The entire apparatus is controlled by a sequence controller with gas measurement intervals that can be set at different rates.

Field results indicated that the TCG monitor will be useful for fault monitoring [22].

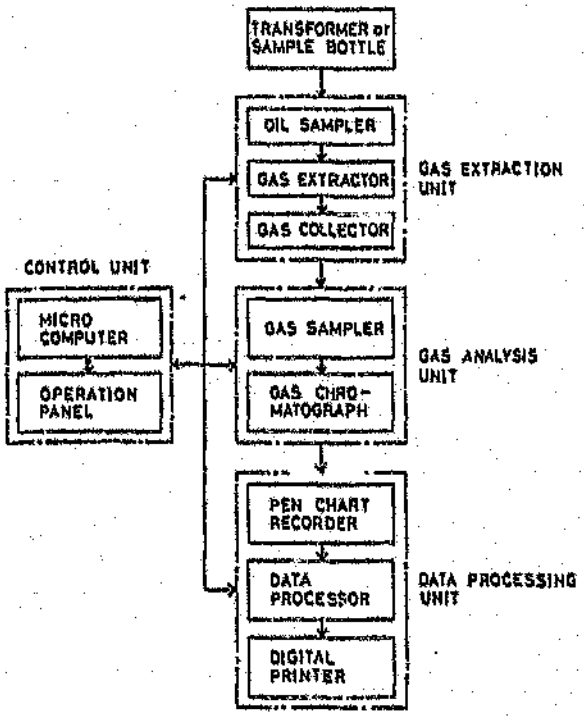


Figure 5.5 Block diagram of TCG apparatus

5.4 Complete transformer monitoring system

A complete transformer monitoring system aims to monitor all possible transformer problem areas. This type of system is used to determine the existence of a fault rather than diagnose its origin.

Westinghouse has developed the Transformer Monitoring System (TMS) to provide continuous on-line monitoring and analysis of selected power transformer operating parameters. Figure 5.6 is a block diagram of the system. TMS has the following inputs:

- Top oil temperature - uses two Platinum Resistance Temperature Detectors (RTD).
- Winding current - uses an instrument current transformer (ICT).
- Relative corona - uses an acoustic corona detector.
- Gas-in-oil hydrogen concentration measured by continuous gas analyser.
- Status inputs - contact closures from various indicators, which include : oil level, oil flow, bearing status of oil pumps.

The use of multiple inputs, continuous monitoring, and an historic data base improves the availability and utilization of power transformers [23].

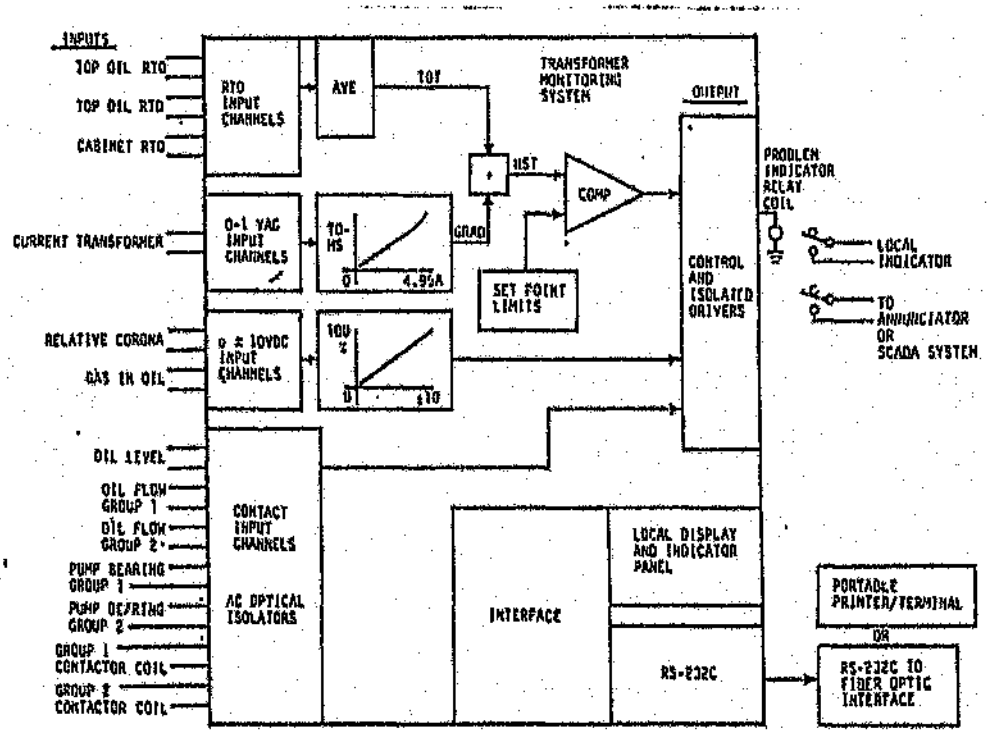


Figure 5.6 Functional diagram of TMS

6 CONCLUSION

Gas-in-oil analysis as opposed to other techniques is well proven and reliable in determining the condition of insulation.

Partial discharge measurements are not reliable, because even though an higher partial discharge measurement will indicate an higher probability of a fault, there is no definite correlation. Also, the background noise is very high in the field, and can easily swamp out the actual measurement. An exception to this is a technique developed for current transformers connected to a common bus that allows the common noise to be filtered out. This is only useful for transformers close together on a common bus.

Power factor measurement is not easily implemented in an on-line monitor. Since power factor measurement is a bulk measurement, localised faults are not easily detected. Research also shows that the power factor does not necessarily increase in the presence of a fault, while the hydrogen gas definitely does increase.

Acoustical Emission Analysis is still in its infancy, and therefore its usefulness for on-line monitoring is still limited.

High Performance Liquid Chromatography promises to be useful in the future, but lacks the development of Gas Chromatography. Also an on-line monitor built on HPLC principles will be bulky and expensive due to lack of off-the-shelf parts.

The design approach to an on-line monitor will be based on the following considerations:

- Because of the number of transformers in the field, the cost of the on-line monitor is very important, especially with respect to the cost of the transformer.

- the on-line monitor is also cost sensitive in terms of the University budget for the project.
- The design should be reliable and based on sound theoretical and practical considerations.

Due to the cost of large transmission and generation transformers, the cost of the on-line monitor is less of a problem. Therefore it is desirable to go for a full blown hydrocarbon on-line monitor using some ratio test.
Designing and building such a monitor will be duplicating commercially available designs and there is the problem of a limited University budget.
On the other hand designing and building an on-line monitor for current transformers has the following advantages:

- There is a very definite need for current transformer on-line monitoring due to the amount of recent failures.
- Current transformers are cheap and therefore require a very cheap on-line monitor design.
- Even though there are commercially available designs, they are very expensive. (more than R25 000).
- There is a total lack of information on gas limits, ratio limits for current transformers. The information provided in the previous chapters are almost exclusively for high voltage transformers.
- Also there is very little information on where the oil sample should be taken. (even for high voltage transformers).

In conclusion, the design of an on-line monitor will be for a low cost gas-in-oil type for current transformers. Because of the cost considerations, only one gas will be monitored. The overwhelming evidence points to hydrogen as being the most suitable gas for detection.

Experiments will have to be done to determine for what rates and upper limits of hydrogen production alarms will have to be set, and where the oil should be monitored in the current transformer.

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APPENDIX B

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1 INTRODUCTION AND HISTORY

Appendix B has been written as a self-contained document, and therefore includes its own index and references. A description of all the apparatus used to perform the experiments is given.

This document, while fulfilling part of the MSc(ENG) dissertation requirements, will prove very useful for anybody continuing research into this field. The apparatus built should prove very useful for future experimentation.

The apparatus used is described in six different sections :

- Experimental Tank - This apparatus is used to simulate a CT (Current Transformer). It allows on-line monitors to be bolted on at various heights, while in contact with the oil, or air space above the oil.
- Hydrogen G.I.O. (Gas-in-Oil) on-line monitor - A description of the physical construction of the monitor, and the internal electronics is given.
- Gas-tight calibration chamber - This chamber allows various hydrogen sensors to be calibrated.
- Hydran - This commercial hydrogen on-line monitor was used to complete some of the experiments. A description of the principle used is given, followed by a description of the physical construction and internal electronics.
- Hydrogen sensors - A description of both the Sieger, and the Figaro sensors are given.
- Datalogger - Initially a self-contained datalogger was designed and partially built. Due to a change in the direction of the MSc(ENG) work, this was not finished. A commercial datalogger was used instead. A description of both will be given.

To provide the reader with a better overall view of the project, the history background to the acquisition of the various apparatus is given.

The overall aim of the project was to build a low cost G.I.O. (Gas-in-Oil) on-line monitor, and use that to test the response of a monitor mounted at various heights on a mock-up of a CT (current transformer) - the experimental tank.

This called for 3 distinct apparatus : an experimental tank, an on-line monitor, and some form of datalogging facility.

Due to cost considerations, the on-line monitor was based on a membrane technique to separate dissolved hydrogen gas from the oil. The on-line monitor requires two components, the hydrogen sensor and the membrane, which are the most difficult components to locate. Initially the only hydrogen sensor that could be located was the Figaro sensor, a resistant element gas sensor. This had to be ordered from Japan. No suitable commercial membrane could be located. While the sensor was on order, the experimental tank was designed and built. For cost reasons, the experimental tank was built out of PVC. Four ports were welded on at various heights, which allows an on-line monitor to be mounted at these heights.

Once the Figaro sensor arrived from Japan, the on-line monitor was designed and built. The on-line monitor was turned out of aluminium and steel. To allow the on-line monitor to be interfaced to the ports of the experimental tank, aluminium flanges were made that bolted to the ports.

When the project was started, it was envisaged that the datalogging side would be a large portion of the work. A prototype datalogger was built around a commercially available microprocessor board. A self-contained microprocessor board was then designed. At this stage it became clear that the problems associated with the the actual G.I.O. monitoring were more important. The final product was therefore not implemented. Fortunately a Fluke datalogger was kindly loaned by the Process Control Group of E.I. (Engineering Investigations).

E.I. was approached for help in obtaining a suitable membrane. Mr. G. Lok from Applied Chemistry at that stage was building up expertise in membrane technology. Applied Chemistry kindly supplied a membrane based on experimental technology. (In the meantime, this technology has been patented.)

Initially standard sample tins were used to take oil samples from the experimental tank. Problems were encountered with the reliability of this method for the hydrogen gas. To eliminate any possible errors due to the sampling technique, two gas-tight syringes were ordered from America. To use these on the experimental tank, various interfaces were made.

At about this stage of the MSc(ENG), a different hydrogen sensor (Sieger), a fuel cell gas sensor, was obtained. This was used to monitor the hydrogen gas level in the air space above the oil in the experimental tank.

Various electronic interfaces were considered for the on-line monitor. Eventually the standard 4-20mA loop was used. Once the on-line monitor was completed, it was tested on the experimental tank. The experimental results were negative. (See Appendix C, Experiment 2 for more details.) To check this, the Hydran was borrowed. An adapter had to be made that allowed the Hydran to be bolted to the experimental tank. The results again were negative.

To solve this problem, the sensors had to be tested in a more controlled experiment. The gas-tight calibration chamber was then built to calibrate the sensors and test the Hydran.

Note : See Appendix C for details of all the experiments done.

In the next few chapters, the apparatus used are described in detail. This is finally followed by the recommendations for the further use of these apparatus.

2 EXPERIMENTAL TANK

The experimental tank was designed to allow on-line monitors to monitor the hydrogen concentration in a controlled experiment. The problems in using an actual CT are :

- Safety hazards from live apparatus.
- Difficulty in accessing actual conditions within the CT.
- Difficulty in gaining access to the oil, and air space above the oil.

Once the experiments can be reliably performed on the tank, these can then be performed on an actual CT.
Note : the experimental tank can be equally well used to simulate the conditions within a HV transformer.

The tank allows various on-line monitors to be bolted on at different heights. The Sieger sensor can be bolted to the bottom of the top lid. This allows the hydrogen concentration in the air space above the oil to be monitored. The output from the Sieger sensor and the on-line monitor are 4-20mA current loop outputs. This easily interfaces to the Fluke datalogger via a load resistor.

A partial discharge or arc can be created in the oil to simulate a fault. This can be done at any desired height in the oil. The amount of partial discharge or arcing can be monitored on the partial discharge monitor. Unfortunately the total energy expended in a fault cannot be directly read from the partial discharge monitor, only the maximum level of the fault.
For more accurate studies, the apparatus was modified to allow a direct injection of a known amount of hydrogen gas into the oil.

See Figure 2.1 and Figure 2.2 for a diagram and photo respectively of the complete system.

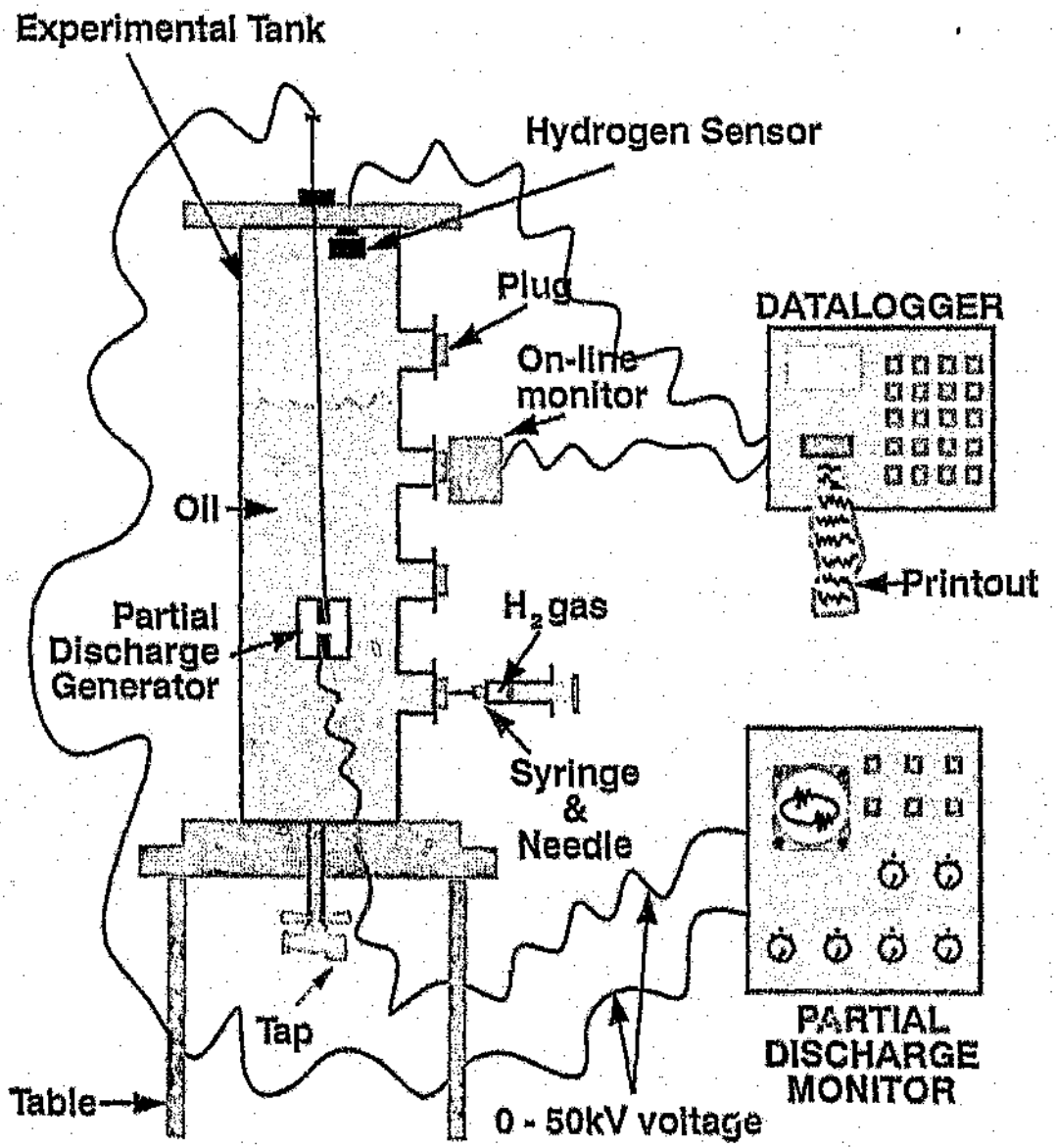


Figure 2.1 Block diagram of the complete experimental set-up



Figure 2.2 Photo of the complete experimental set-up

2.1 Description of the physical construction of the tank

The experimental tank was made 1.5 metres high, and 30cm in diameter. See Figure 2.3 for the diagram of the tank. Four ports are welded on at various heights. See Figure 2.4 for close-up of port. The ports are welded on via a short length of pipe from the tank. This is closer to the situation when an on-line monitor is used on a real CT.
The top lid and bottom lid are bolted to the tank via rubber gaskets. A brass rod, that is connected to the partial discharge generator, goes through the middle of the lid via a cable gland. The Sieger sensor is also bolted to the bottom of the lid. See Figure 2.5 and Figure 2.6 for more details.
The complete tank is supported on a small table. A tap at the bottom of the tank allows oil to be drained out. See Figure 2.7.

A large effort was expended in making the tank as air tight as possible. If the experiment calls for an air breathing experiment, the top port can be left open to the air. Between both the bottom lid and tank, top lid and tank, a soft rubber gasket was used. Between the aluminium flanges and the ports, o-rings were used. Teflon tape was used on all the screw threads. This included the screw thread on the on-line monitors, plugs, Sieger sensor and tap. Petroleum grease was used on all the gaskets and o-rings.

2.2 Description of the partial discharge generator

A brass rod allows the partial discharge generator to be lowered into the tank at any desired height. This allows faults to be simulated at various heights. The live connection is made to the brass rod at the top. The return lead is taken through the bottom of the tank via a screw. If the partial discharge generator is not used, the hole in the top lid can be blocked with a plastic plug.

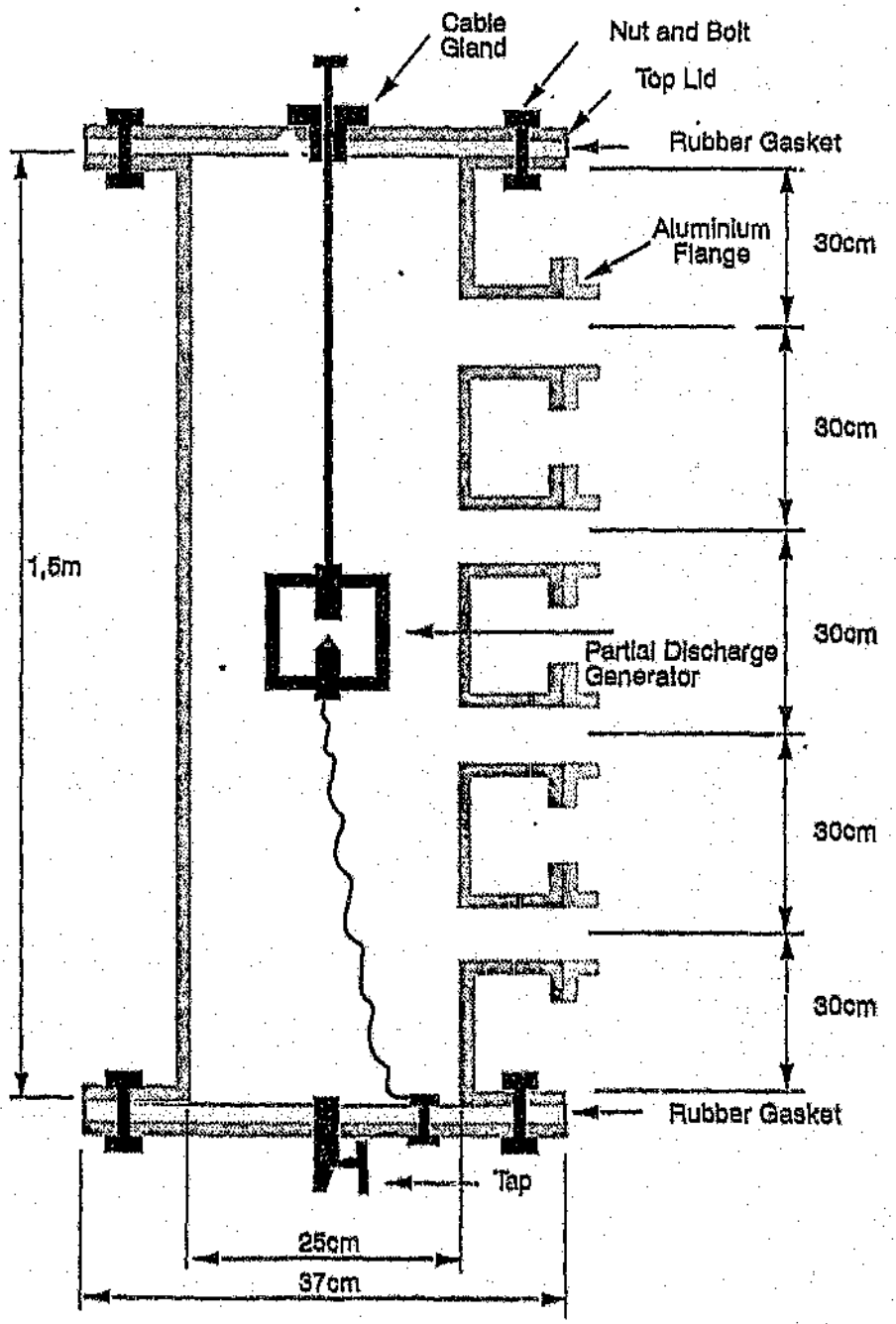


Figure 2.3 Diagram of experimental tank



Figure 2.4 Photo of a port

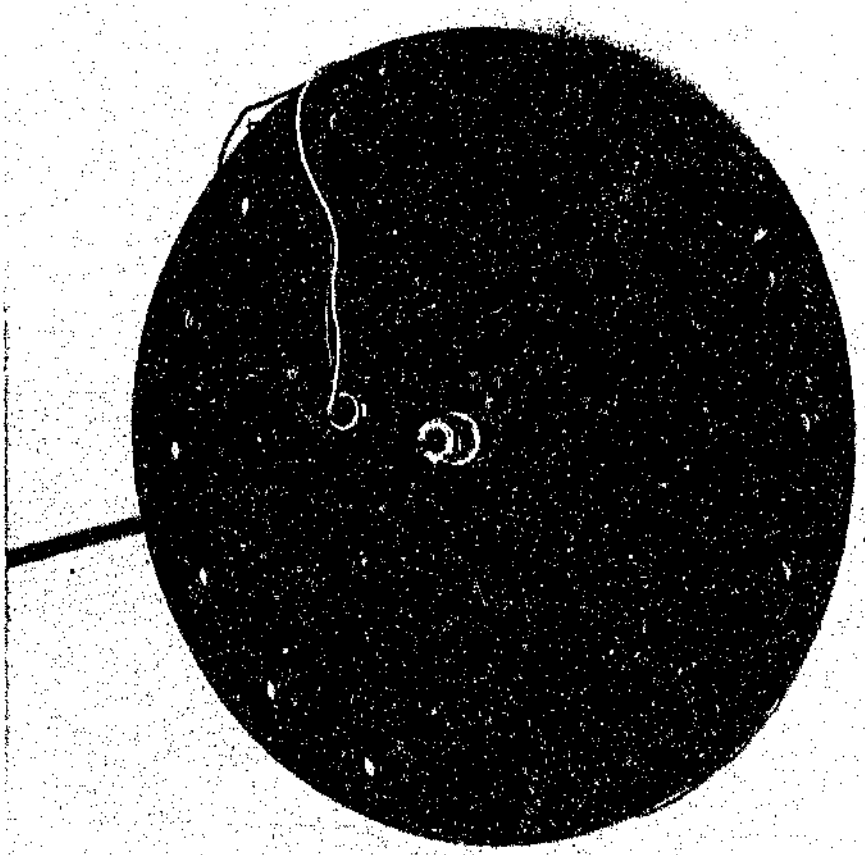


Figure 2.5 Photo of the top lid - upperside

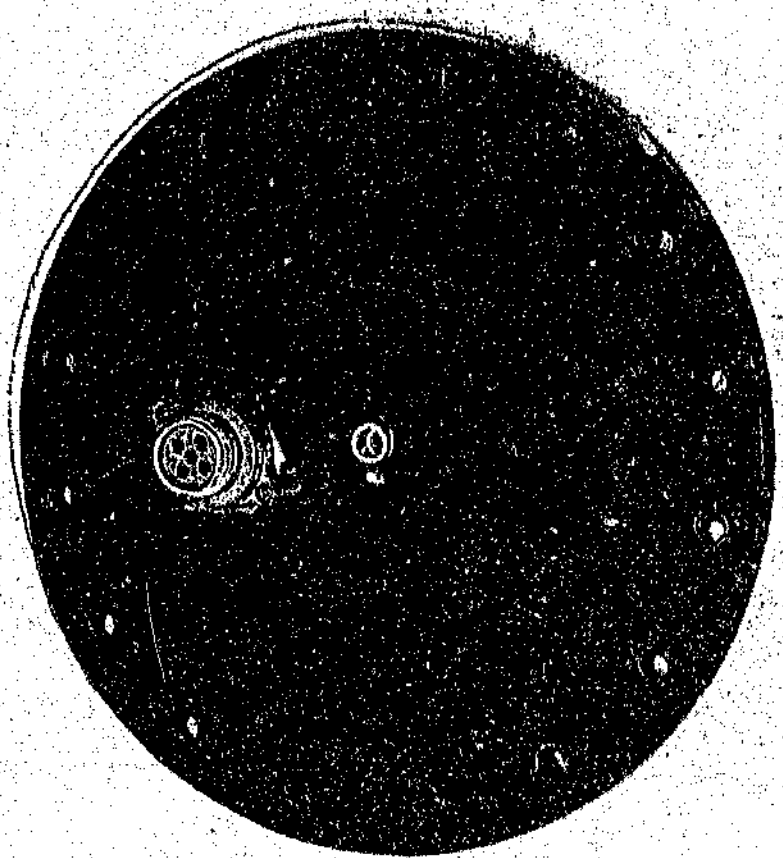


Figure 2.6 Photo of the top lid - lowerside

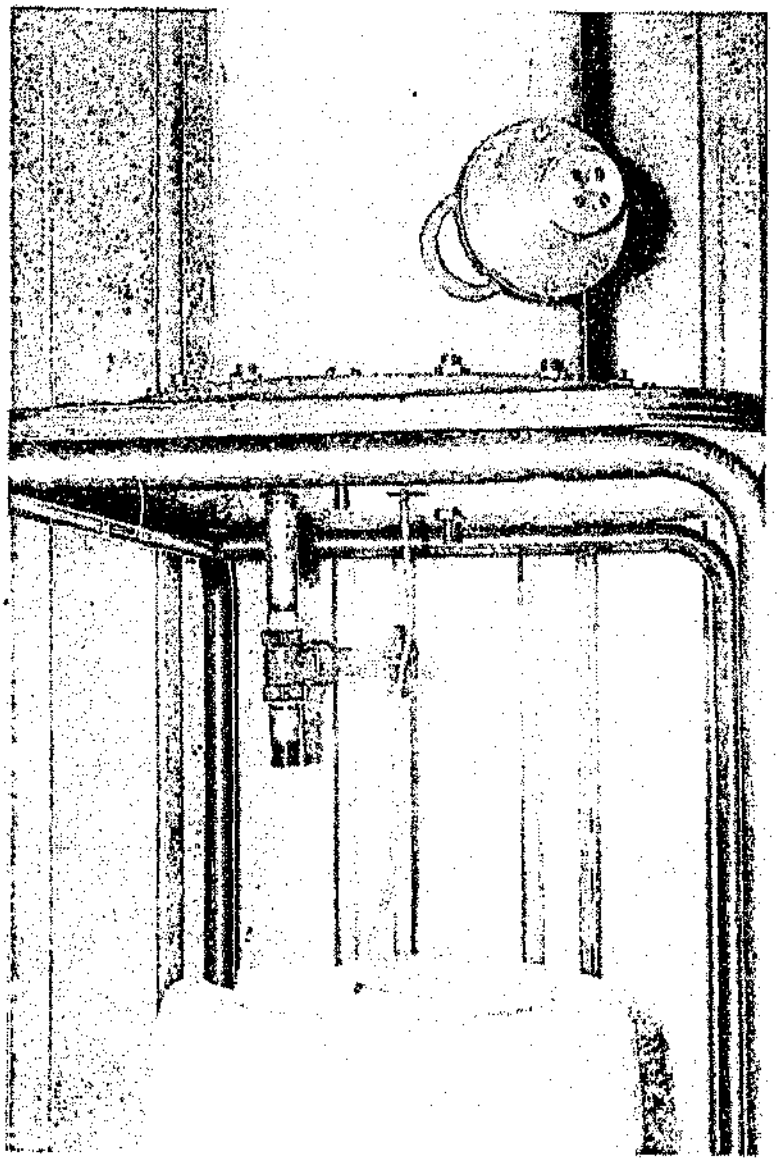


Figure 2.7 Photo of the bottom of the tank

The partial discharge generator consists of a Perspex body. Two brass screws, specially shaped, screw through the top and the bottom of the Perspex body. See **Figure 2.8** and **Figure 2.9**. The screw with the sharp point screws into the bottom of the Perspex body, and the screw with conical hole screws into the top of the Perspex body. The conical hole faces down into the oil. An air bubble is trapped in this hole. This allows partial discharge to take place between the two brass screws. Paper can also be sandwiched between the brass screws. The brass rod screws into the top brass screw. This rod holds the complete assembly in the oil. It also provides a path for the live connection to the high voltage power supply. The return connection is made with a wire bolted to the bottom brass rod. This wire is bolted to a screw that is screwed through the bottom lid of the tank.

2.3 Description of the port flanges and adapters

Each port has an aluminium flange bolted to it. See **Figure 2.10**. The on-line monitor built can be directly screwed onto this. A brass adapter allows the Hydran to interface to the flange. See figure 2.11.

Unused ports can be sealed off with brass plugs. These brass plugs have been modified to allow a gas-tight syringe with a needle (**Figure 2.12**) to inject hydrogen gas in the oil. This is done by sandwiching a septa between the brass plug, and an aluminium disc. See **Figure 2.13** for picture of a assembled plug, and the constituent parts of the plug. Initially this system was also used to sample oil from the tank. Unfortunately the needles obtained were too narrow for the oil to easily be drawn in. The brass plugs were again modified, this time to allow the syringe to be screwed on via a small valve. See **Figure 2.13** for the complete plug assembly, and the constituent parts.

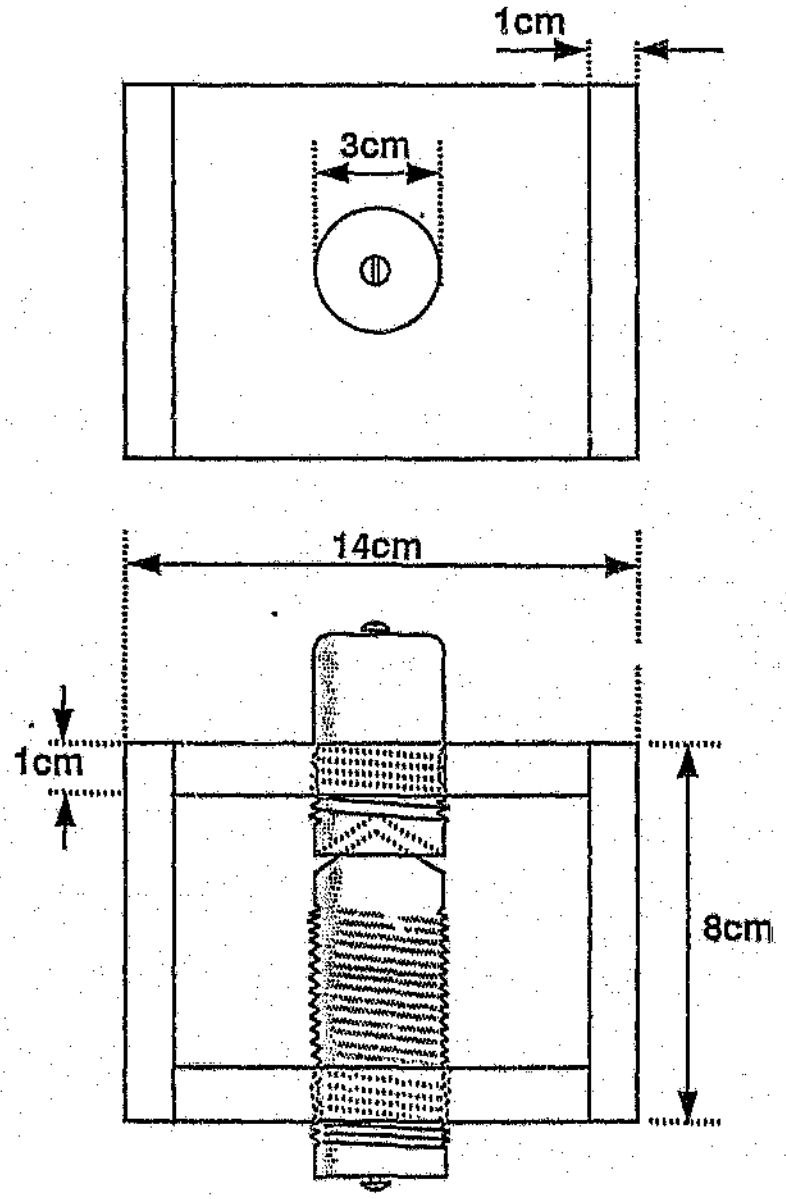


Figure 2.8 Diagram of the partial discharge generator

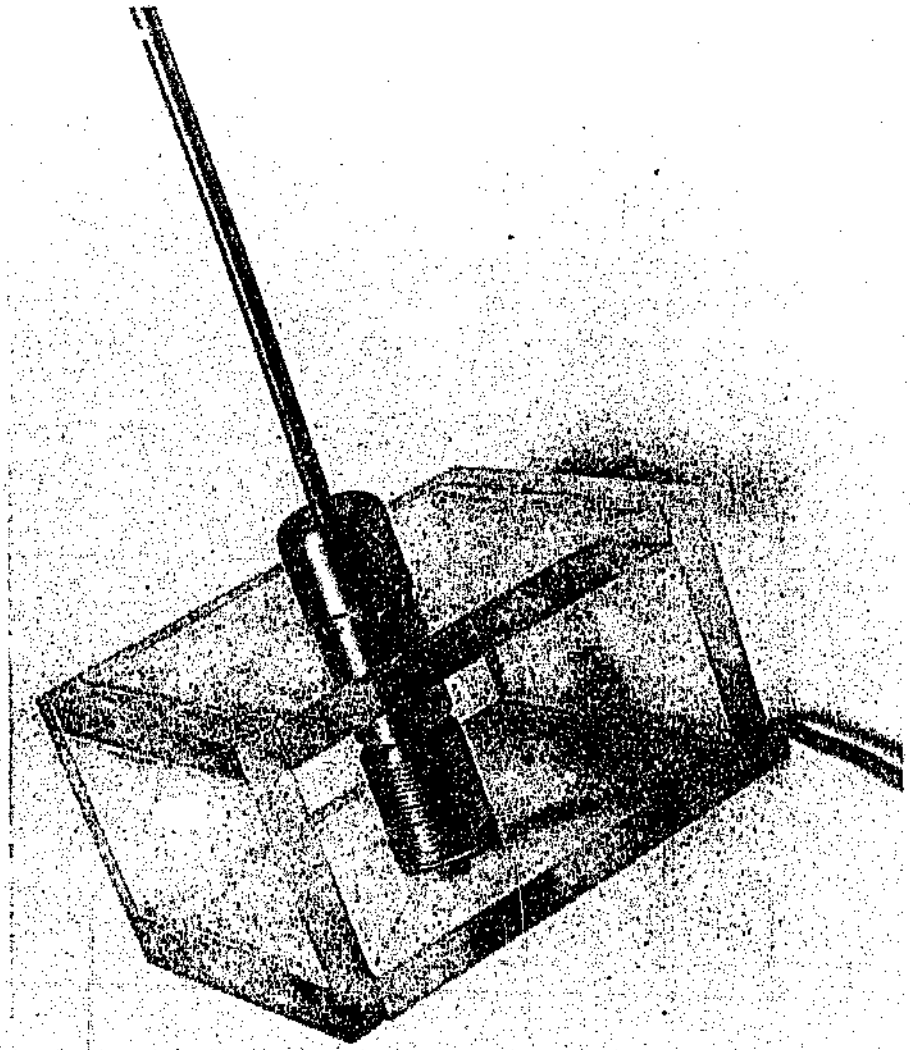


Figure 2.9 Photo of the partial discharge generator

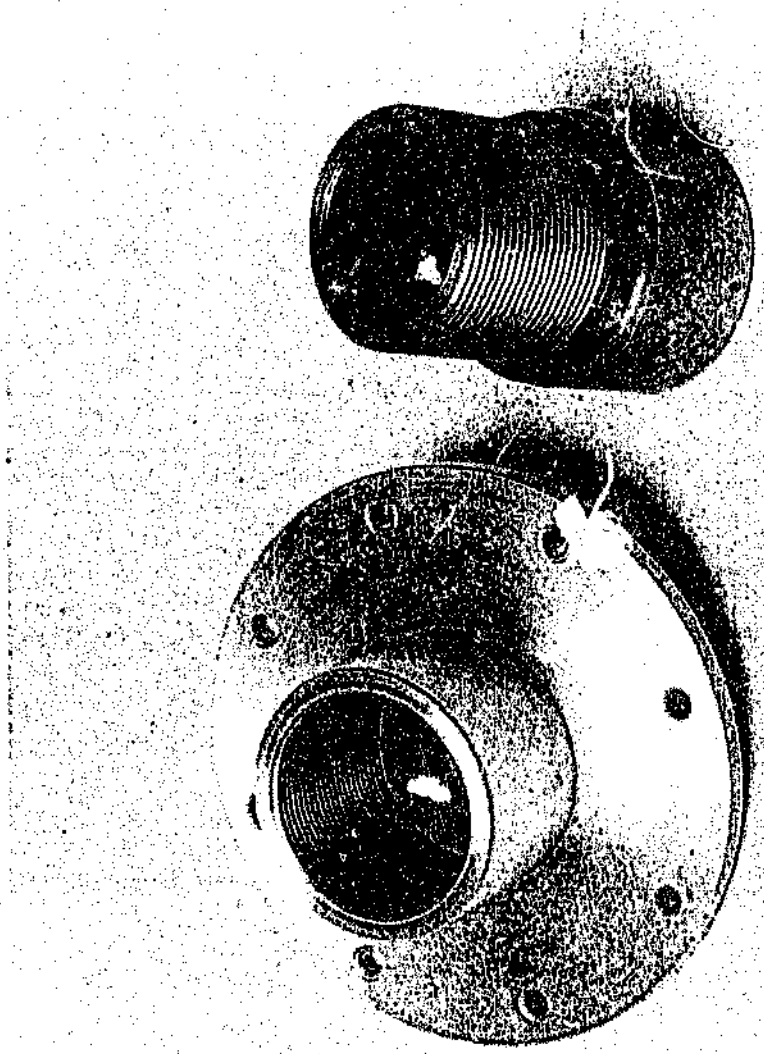


Figure 2.10 Photo of the flange and the Hydran adapter

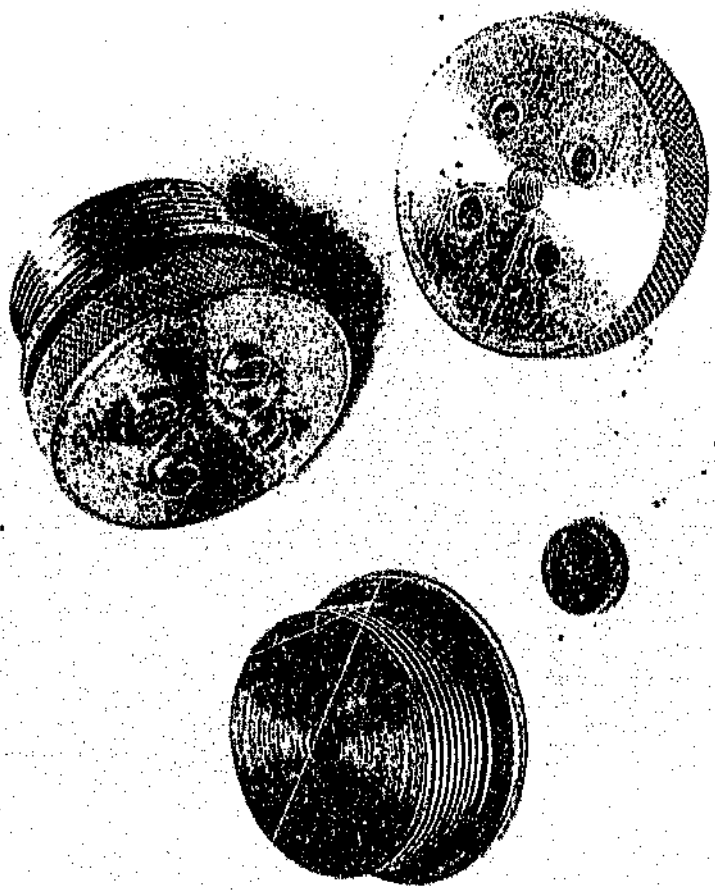


Figure 2.11 Photo of a plug, and its constituent parts (for use with the syringe via a needle)



Figure 2.12 Photo of the sampling syringe and needle



Figure 2.13 Photo of a plug, and its constituent parts (for use with the syringe via a valve)

3 HYDROGEN G.I.O. ON-LINE MONITOR

The monitor housing is divided into 3 chambers. See Figure 3.1. The first chamber is in contact with the oil. The gases dissolved in the oil diffuse through the membrane into the gas chamber. The gases come in contact with the Figaro sensor which is mainly sensitive to hydrogen gas. The output from the sensor is converted to 4-20mA industry standard current loop. A temperature sensor is mounted next to the Figaro sensor. The output from this is also converted to a 4-20 mA industry standard current loop.

The basic principle of operation is that the gases dissolved in the oil will diffuse through the membrane into the gas chamber. Once equilibrium is reached, the ratio between the concentration of hydrogen in the oil, and in the gas chamber will be equal to the Ostwald solubility coefficient for hydrogen. Therefore the reading from the Figaro sensor should be proportional to the concentration of the hydrogen gas in the oil.

3.1 Description of the physical construction

The on-line monitor is made of aluminium, except the part that screws onto the flanges that are bolted to the ports. This made of steel. See Figure 3.1 for cross-sectional picture of the monitor. See Figure 3.2 for a picture of the assembled monitor, and Figure 3.3 for the constituent parts.

The membrane separates the oil and the gas chamber. The membrane was specially manufactured by the Applied Chemistry Department of E.I. Unfortunately, the details of the membrane's composition or construction cannot be given, as it was been patented at the time this report was written. The most important detail of the membrane is that it has been made to be as permeable to gases as possible.

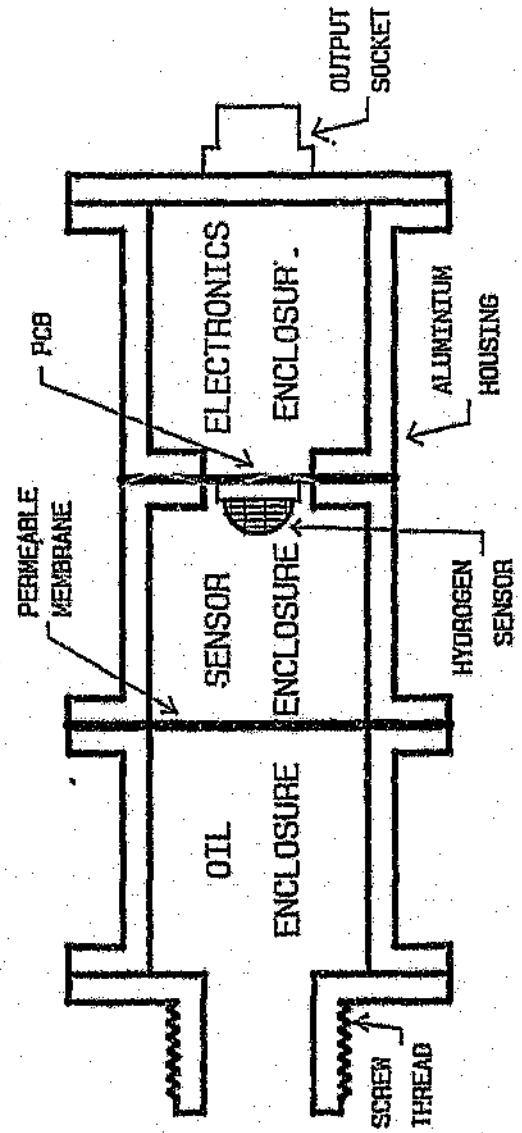


Figure 3.1 Cross section diagram of the hydrogen on-line monitor

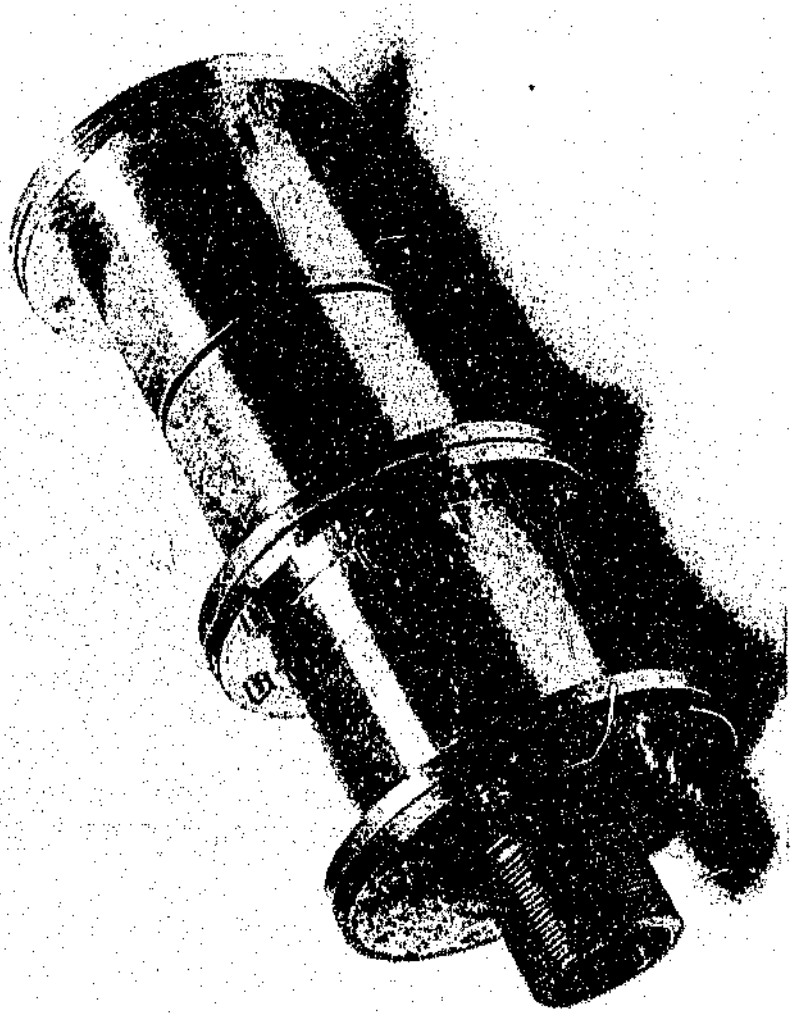


Figure 3.2 Photo of the assembled on-line monitor

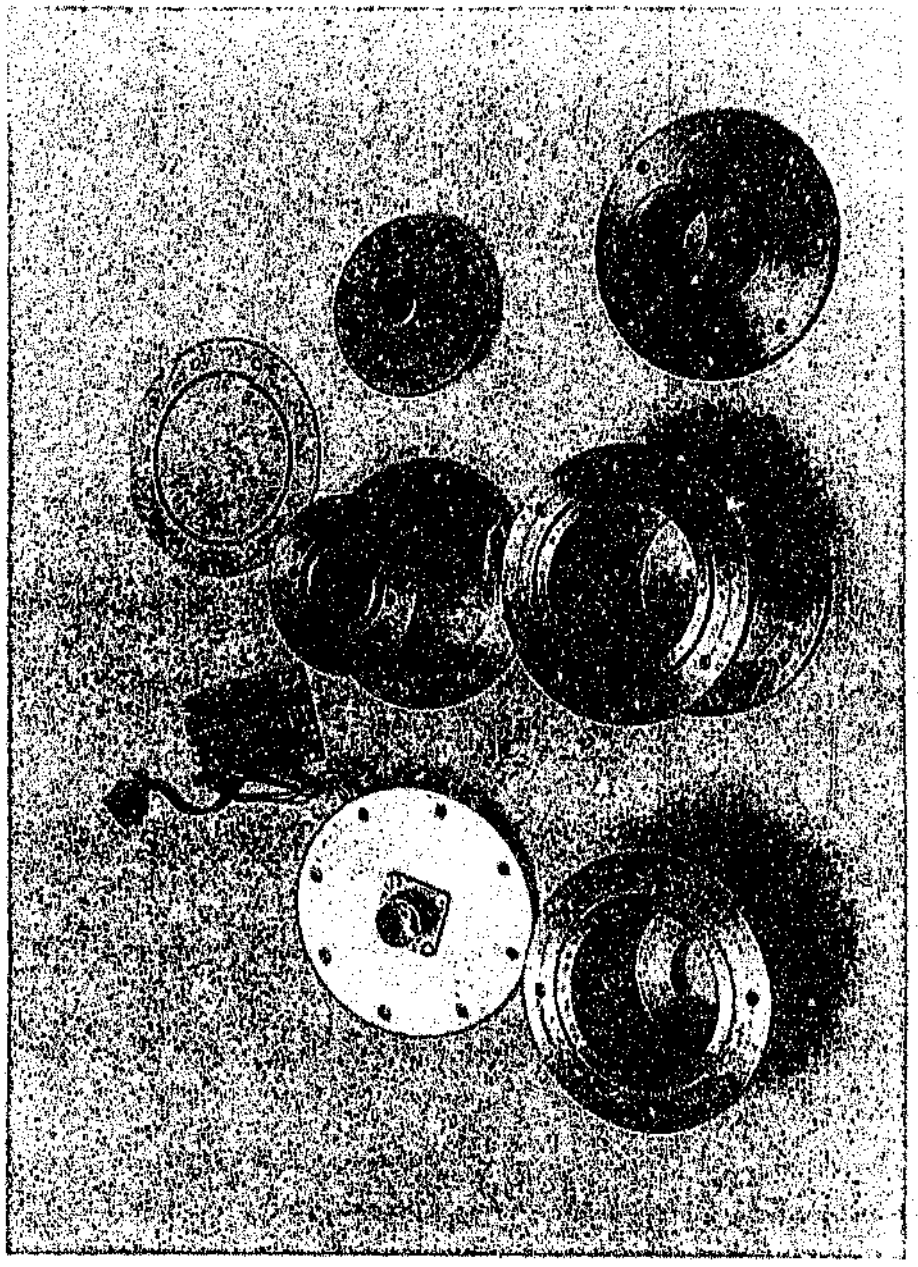


Figure 3.3 Photo of the disassembled on-line monitor

Both sensors are mounted o.. a PCB (Printed Circuit Board) that separates the gas chamber from the electronic chamber. The main interface electronics is mounted onto a second PCB, which is held in the electronics chamber. A water resistant socket is used for the output from the electronics.

The complete unit is made as gas-tight as possible, Each chamber is also sealed from the other with o-rings.

3.2 Description of the electronics

See Figure 3.4 for the block diagram of the electronics. The Figaro sensor requires a stable 5V at 150 mA power supply for the heater element, therefore the incoming power supply must be regulated. A normal regulator cannot be used, because the heat cannot be dissipated in the confined enclosure. A small state-of-the-art switchmode power supply is used. The output from the Figaro sensor is buffered, before going into the voltage-to-current converter IC (Integrated Circuit). The precision reference for the sense element in the sensor is also supplied by the IC. A second voltage-to-current converter IC is used for the temperature sensor. The temperature sensor is positioned right next to the Figaro sensor. All input and output connections are protected from noise and overvoltage. See Figure 3.5 for the complete circuit diagram. See figure 3.3 for a picture of the Figaro sensor PCB (Printed Circuit Board), and the electronic PCB.

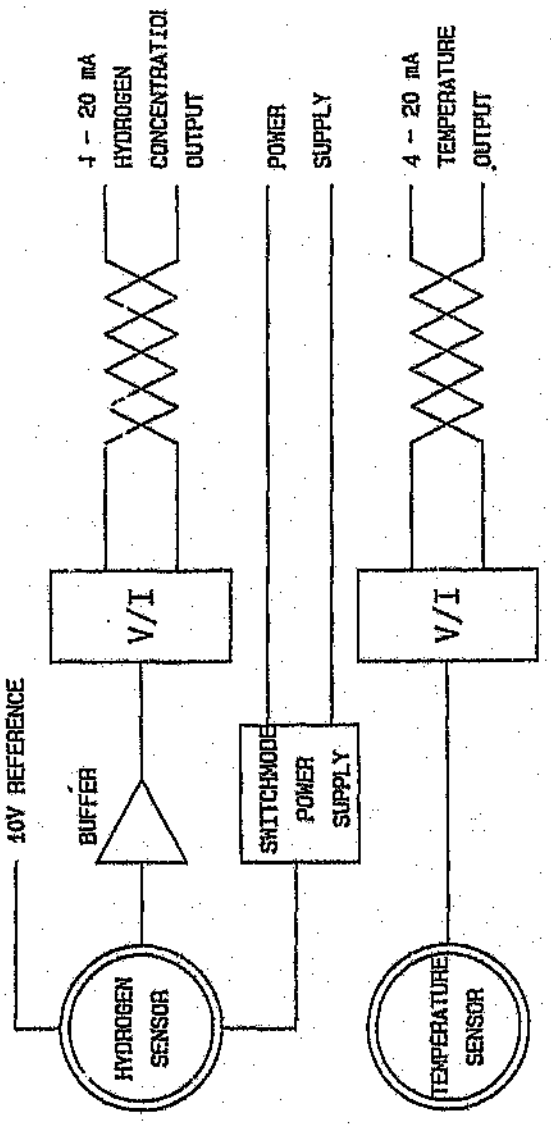


Figure 3.4 Block diagram of the monitor's electronic circuit

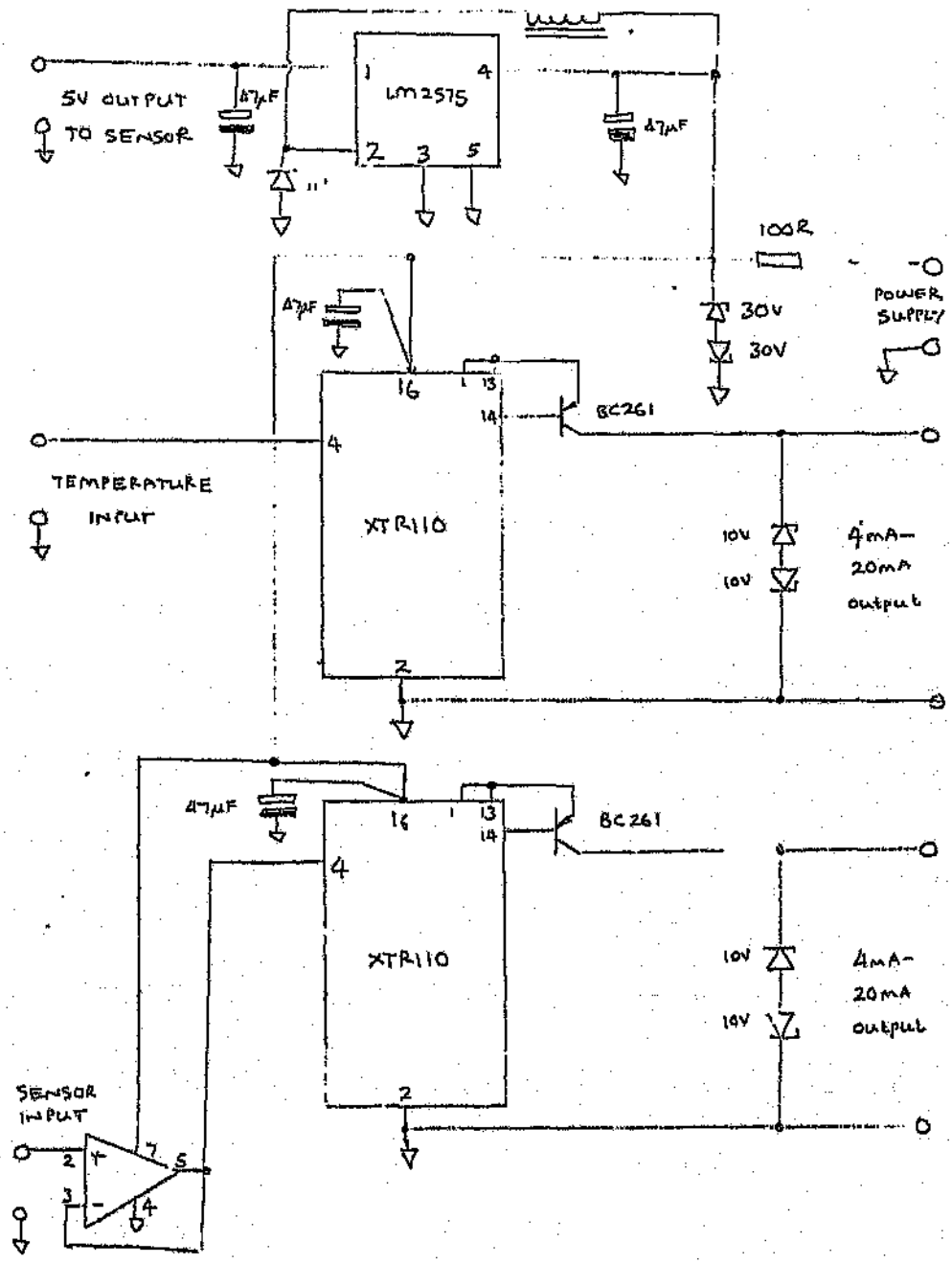


Figure 3.5 Complete diagram of the monitor's electronic circuit

4 GAS-TIGHT CALIBRATION CHAMBER

A gas-tight chamber had to be constructed to calibrate the Figaro sensors. A known amount of hydrogen gas is injected into the chamber. The concentration of the hydrogen gas is then the quantity of the hydrogen gas injected divided by the volume of the chamber.

To increase the versatility of the chamber, the chamber has a port, the exact same size as one of the ports on the experimental tank. One of the aluminium flanges used on the tank, is bolted to this. This allows the Sieger sensor to be screwed into this port, or via an adapter, the Hydran. If this feature is not used, the port can blocked off with one of the brass plugs. The Sieger sensor is bolted onto the ports, and the Figaro sensors are inside.

The chamber can also be filled with oil. Hydrogen gas can be injected into the oil. A magnetic stirrer is used to mix the hydrogen gas and the oil. (Note : Great difficulty was found in mixing the oil and the hydrogen gas. See Appendix C.)

4.1 Description of the physical construction

The complete chamber is made of Perspex. All the sides are glued together, except for the lid. This bolts onto the top with screws. An o-ring is used to maintain a gas-tight seal. A circular disc of Perspex, the same dimensions as a port on the tank, is glued onto the top. This has a hole in the middle that goes through the lid as well. One of the aluminium flanges used on the tank, can be bolted onto this. An o-ring is used to seal the gap between the flange and the Perspe... A similar port, but smaller, is also glued to the lid. A septa is sandwiched between this, and a similar sized Perspex disc. This port allows a syringe with a needle to inject a known amount of hydrogen gas into the chamber.

Eight brass screws are screwed through tapped holes in the top lid. A wire lug is used on both sides of the screw. This allows electrical connections to the inside of the chamber. This was used to test 3 Figaro sensors mounted inside the chamber. To maintain a gas tight seal, Teflon tape was used on the eight screws. See Figure 4.1 for the dimensions of the chamber. See Figure 4.2 for a picture of the chamber.

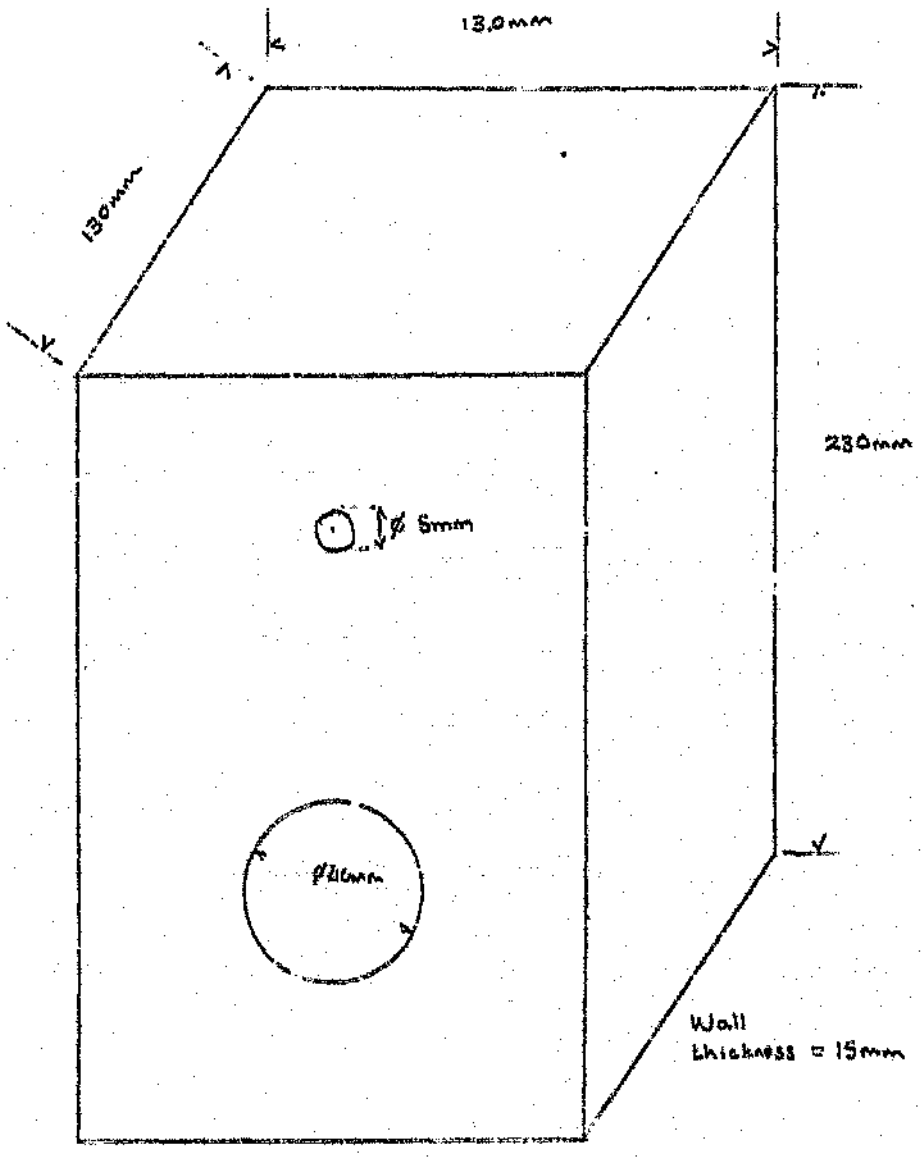


Figure 4.1 Diagram of the gas-tight calibration chamber

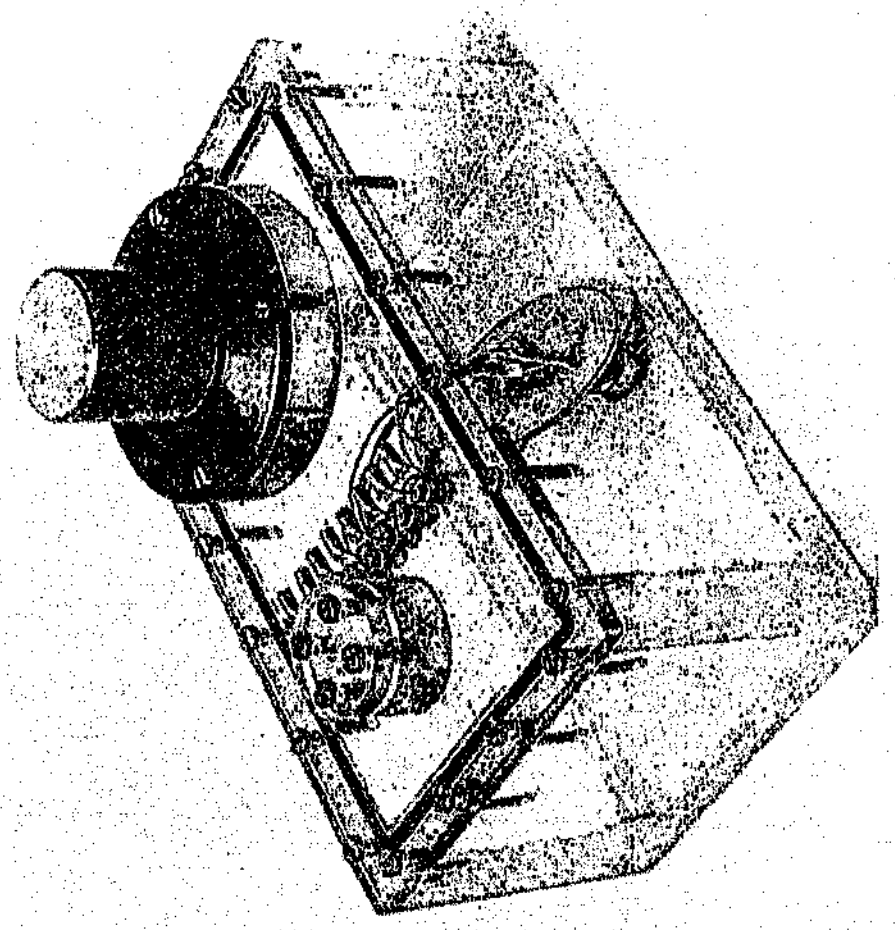


Figure 4.2 Photo of the gas-tight calibration chamber

5 HYDRAN

A commercial hydrogen on-line monitor was borrowed to complete some of the experiments. The Hydran monitor was kindly loaned by the ROTEC group of ESKOM. Because the designed on-line monitor is similar in principle to the Hydran, it was decided to evaluate its performance. These experiments highlight some of the problems with the principle. See Appendix C for more details.

A brief description of the principle of operation for the Hydran is given, followed by a general description of the complete instrument.

5.1 Description of Hydran principle

See Figure 5.1 for a diagram of the cross section of the Hydran. The hydrogen gas dissolved in the oil diffuses through a semi-permeable Teflon membrane and is oxidised electrochemically on a platinum electrode. This electro-oxidation is coupled with the electro-production of oxygen from the ambient air on a second electrode The electric current produced by these reactions is converted into a voltage by a load resistor, which is amplified and displayed by the electronic enclosure.
The sensor is designed so that the hydrogen sensor consumes the diffused hydrogen gas much faster than it can diffuse through the membrane. Thus, the sensor output depends solely on the rate of diffusion through the membrane, which is directly proportional to the concentration of dissolved gas in the oil. [1]

5.2 Description of Hydran instrument

The Hydran instrument consists of the sensor unit, and the electronic enclosure. A black foam sleeve is used, around the sensor unit, to minimise temperature variations.

The sensor contains both a hydrogen sensor, and a temperature sensor. The outputs from both the sensors are sent via a screened cable to the electronic enclosure. These are buffered, and then fed into an analog function IC. This IC allows the temperature output to modify the hydrogen sensor output, so that hydrogen sensor output is decreased as the temperature increases. This is fed to a digital panelmeter, which displays the hydrogen concentration in ppm (parts per million).

The output is also converted to a 0-1mA output for remote monitoring. An optional 4-20mA current loop can also be added.

Two alarm levels can be set. The outputs can be used to warn personnel of an impending fault.

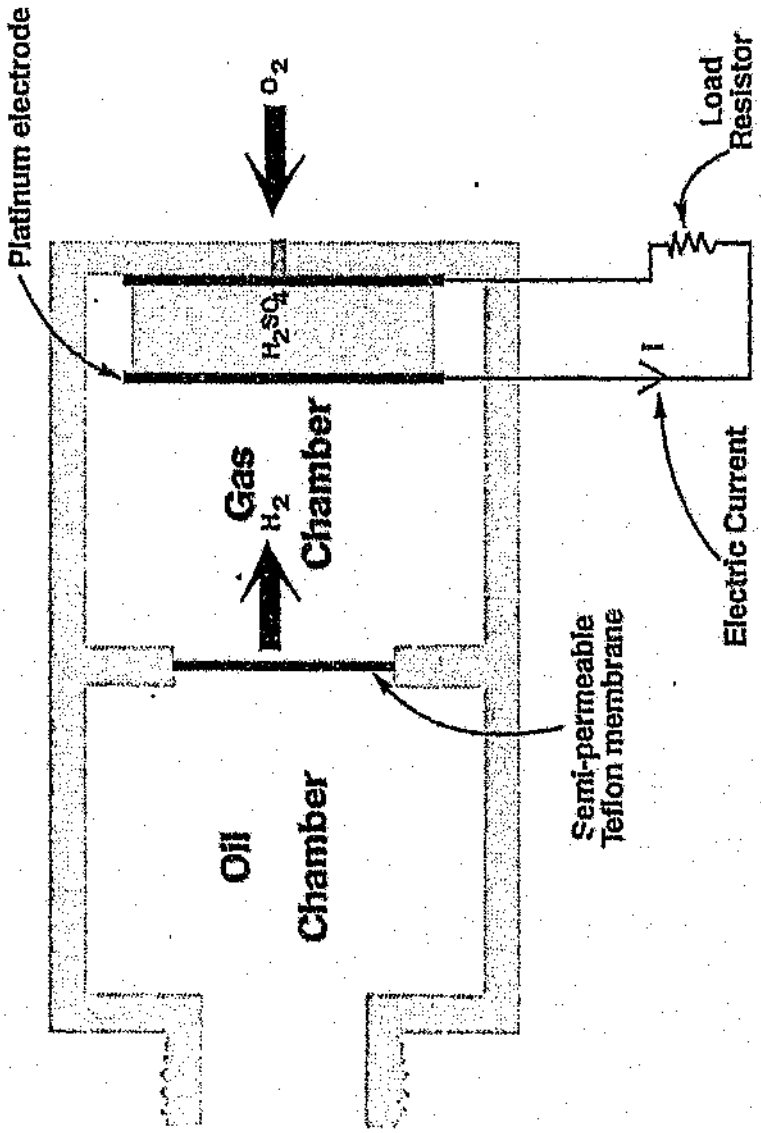


Figure 5.1 Cross-section of the Hydran sensor

6 HYDROGEN SENSORS

Two different sensors were used for the various experiments. Each sensor has its own advantages and disadvantages. A description of both sensors are given, followed by a comparison between the two sensors.

6.1 Description of Sieger sensor

The Sieger sensor is based on the same principle as the hydrogen sensor used in the Hydran. Both use a fuel cell to detect hydrogen gas. See **Figure 6.1** for a cross-section of the sensor.

Note : The Hydran may be using a sensor made by Sieger. This cannot be confirmed, because the Hydran sensor unit cannot be opened.

The hydrogen gas is oxidised electrochemically on a platinum electrode. This electro-oxidation is coupled with the electro-production of oxygen from the ambient air on a second electrode. The electric current produced by these reactions is converted into a voltage by a load resistor. This is amplified and converted by the internal electronics to a current output of 4 - 20 mA output.

The sensor used for the experiments is the model 911. This consists of the fuel cell in a stainless steel housing that will not ignite hydrogen.

The important specifications are :

Standard range	: 0 - 1000 ppm
Response time	: T90 < 70 seconds
Linearity	: Better than ± 5%
Repeatibility	: Better than ± 5% [2]

Note : See reference 2 for more information on the Sieger sensor.
Note : The above specifications were confirmed by SA's largest user of the Sieger sensor - NUCOR.

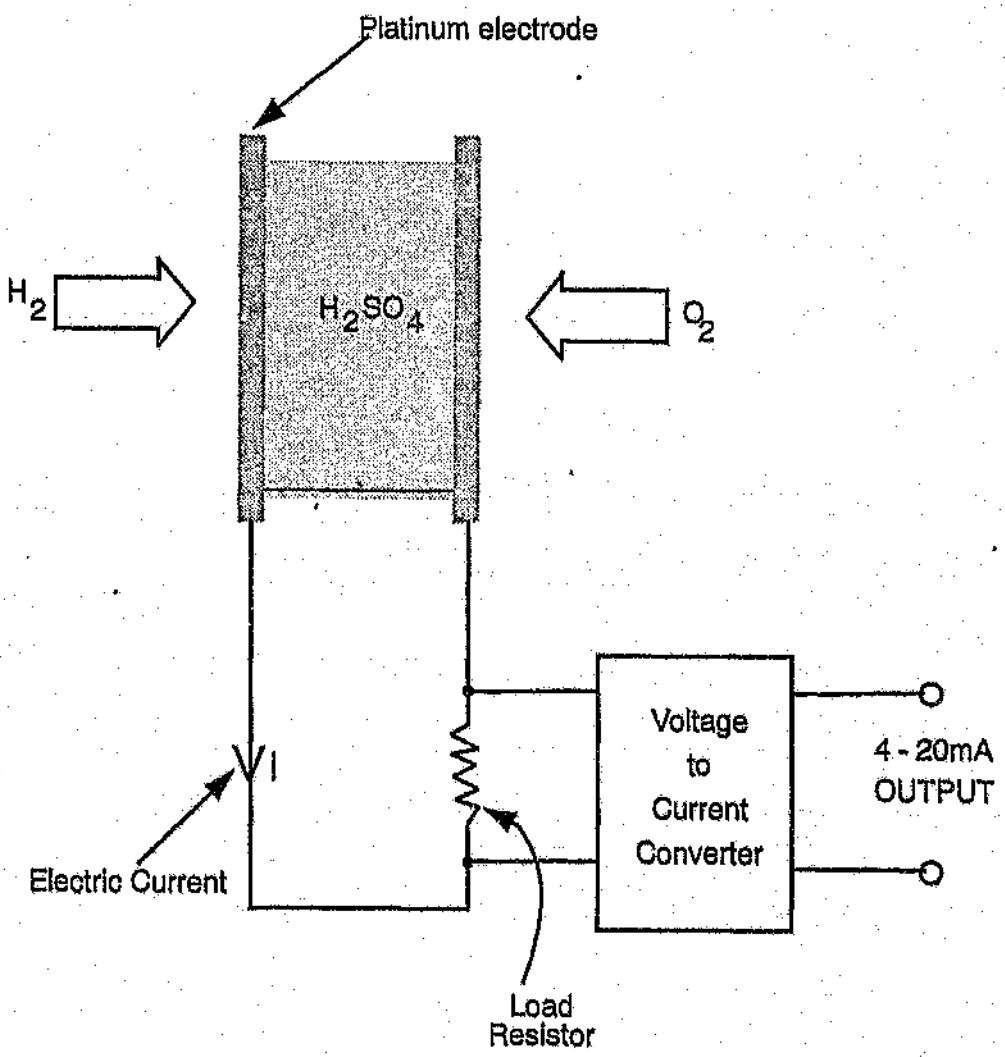


Figure 6.1 Cross-section of the Sieger sensor

Unfortunately the original fuel cell in the Sieger sensor was poisoned, so this was replaced by another cell. This could not be calibrated in SA. When tested on the gas-tight chamber, the output was incorrect.

6.2 Description of Figaro Sensor

The Figaro sensor is based on a resistant element to detect hydrogen gas. The Figaro sensor consists of a tubular ceramic former over which tin oxide is painted. A heater threaded through the ceramic former, maintains a constant temperature along the whole ceramic former. Doped tin dioxide is painted over the surface of the tube to result in an annulus of active material. This element is bonded to the nickel pins of a high temperature resin header. This is held in a nylon case with a stainless steel gauze which will not allow the sensor heater to ignite an inflammable atmosphere. See Figure 6.1 and Figure 6.2.[3]

If a bead of tin oxide is heated in clean air, oxygen is absorbed into the surface layers until an equilibrium condition is achieved for the particular temperature involved. A characteristic conductance for the tin dioxide can be measured, which is a function of both temperature and the partial pressure of the oxygen. If a combustible contaminant gas is present, it will absorb, then react with some of the oxygen, so releasing electrons from the oxygen which become available for conduction. This means that the conductance rises until equilibrium is again attained. The conductance therefore gives a measure of the concentration of the contaminant gas, given conditions of constant temperature and humidity. Clearly any reducing gas will result in a rise in conductance, but a considerable degree of selectivity can be achieved by the addition of catalytic inclusions to the tin oxide and careful control of the temperature.[3]

Note : See reference [3] for a comprehensive report on solid-state gas sensors made by Figaro for more information.

6.3 Comparison between the Sieger and the Figaro hydrogen sensors

Sieger Sensor	Figaro Sensor
Fuel cell has a life of approximately 3 years.	Unlimited life span.
Built in 4-20mA output.	Requires electronic signal conditioning.
Precalibrated.	Uncalibrated.
Expensive : ± R3000.	Cheap : ± R125.

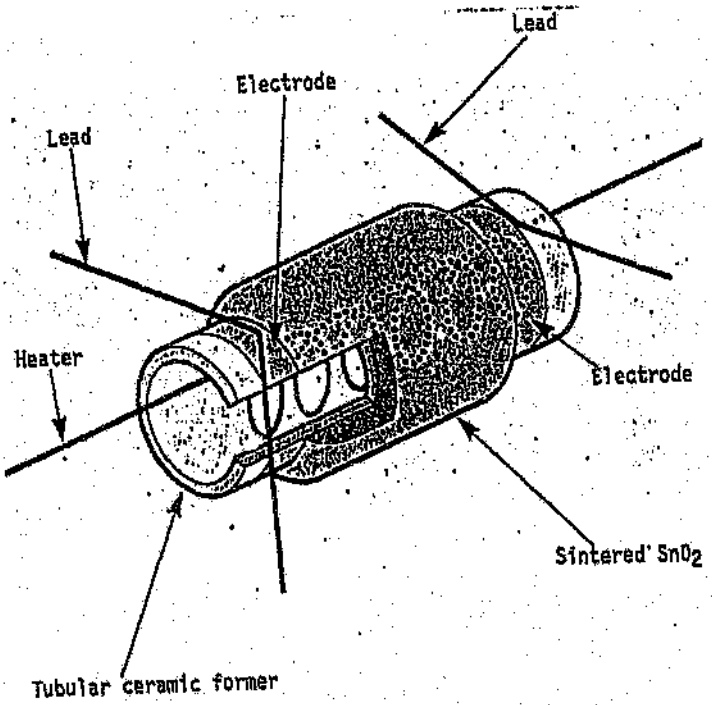


Figure 6.2 Diagram of the Figaro element

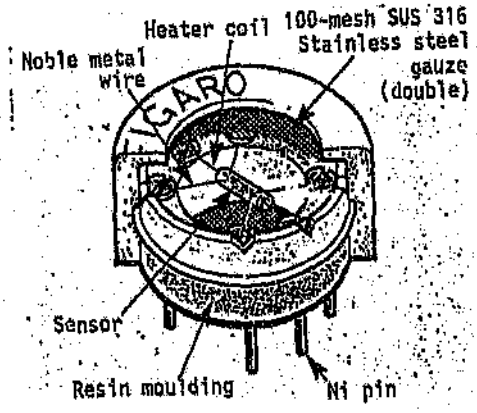


Figure 6.3 Picture of the complete Figaro sensor

7 DATALOGGER FACILITY

When the project was started, it was envisaged that the datalogging side would be a large portion of the work. The datalogger would be a self-contained unit that would allow the readings from the on-line monitor to be logged, and processed for trend analysis. To this end a datalogger was designed around the 80:2AH processor. To test the operation of the datalogger, a commercial board was first used. The core software was written and tested using this commercial board. A more compact board was then designed. At this stage it became clear that the problems associated with the actual gas-in-oil monitoring was more important. To complete the experiments, a commercial datalogger was borrowed. The advantage of the commercial datalogger was that the output was printed directly onto a strip of paper for future reference. An IBM PC computer was required for the designed datalogger to off load the data. An IBM PC was not always freely available for this.

A description of the designed datalogger will be given. This design is definitely still useful for future work as the hardware design is completed. A brief description of the commercial datalogger is then given.

7.1 Description of designed datalogger

A MIC (Murton Industrial Controls) 1017 board was bought to test the initial software. An extra board was built that contained the A/D (Analog to Digital) IC Integrated Circuit). This interfaced to the sensor electronics.

Features of this board include :

- 64K bytes ROM.
- 60K bytes RAM.

- Serial port with auto baud rate selection.
- Choice of RS232, RS422, and RS485 serial interface.
- BASIC interpreter.
- Serial printer port.
- 3 x 8 Parallel ports.
- Onboard EPROM programmer.

This board provided the ideal basis for testing the datalogger. A program could be written on an IBM PC computer, and then downloaded into the MIC micro's RAM via the serial port. Once the program was debugged, the program is programmed into the EPROM.

See Figure 7.1 for the circuit diagram of the A/D board. This based around an 8-bit A/D - ADC0804. The output of the A/D is read by the micro via the parallel ports. The input to the A/D comes from the Figaro hydrogen sensor electronics.

See Figure 7.2 for the initial circuit diagram of the Figaro hydrogen sensor electronics.
Note : This is not the same as the circuit diagram described in Chapter 3.2. The design described in Chapter 3.2 is a later design that is more flexible.

Once the basic software was running, a micro board was designed. This board is obviously cheaper to build than buying the MIC micro board. This design also contains the essential features required for the datalogger, namely :

- 32K bytes RAM for data storage.
- 8K bytes EPROM for program.
- Onboard 8 bit A/D.
- 2 X 8 bit parallel ports.

See Figure 7.3 for the complete circuit diagram.

The software written read the output from the Figaro sensor and the temperature sensor. This was displayed on a 4 digit LED (Light Emitting Di e) display. The hydrogen sensor output was displayed in ppm, and the temperature output in degrees Centigrade. These readings are displayed alternatively every 1 second.

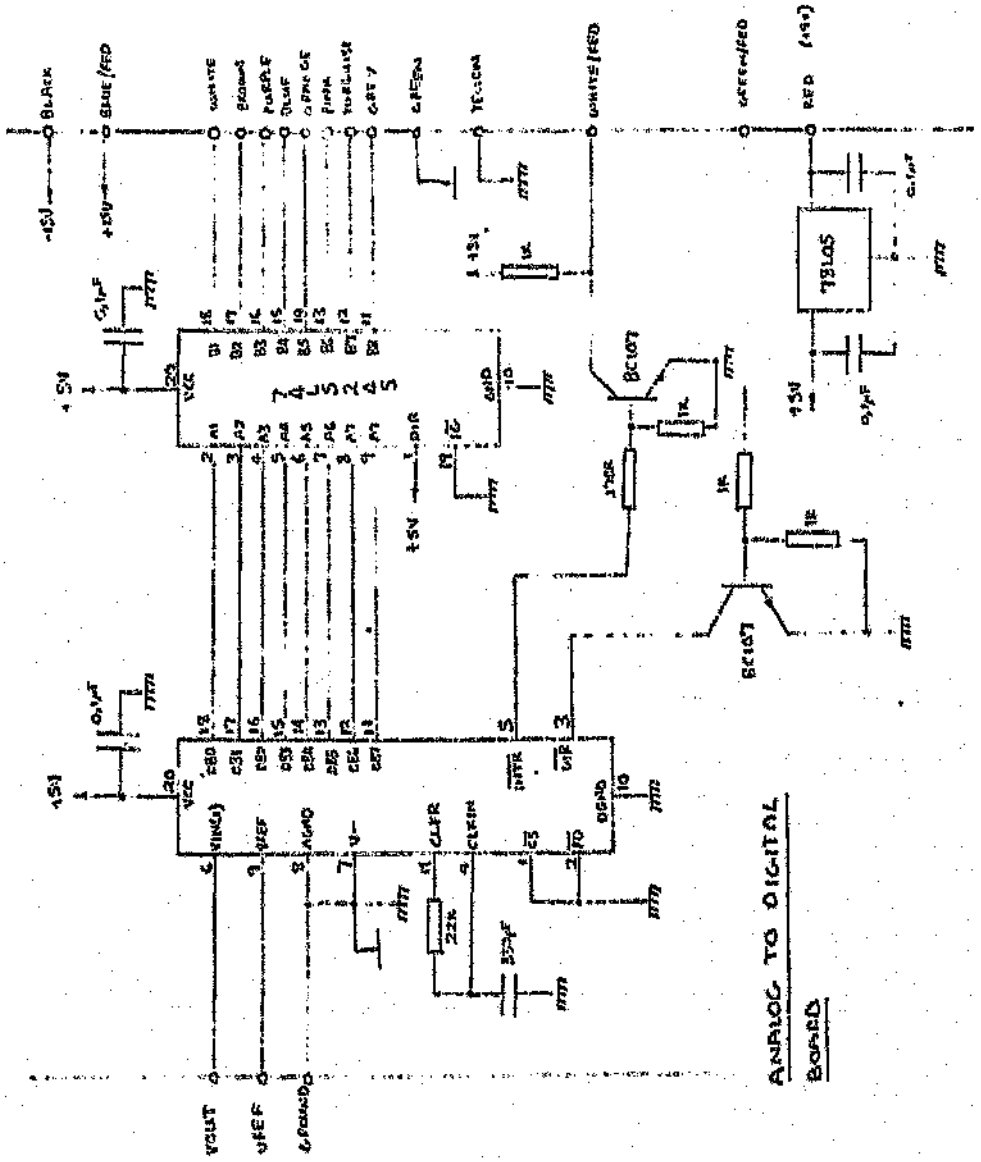
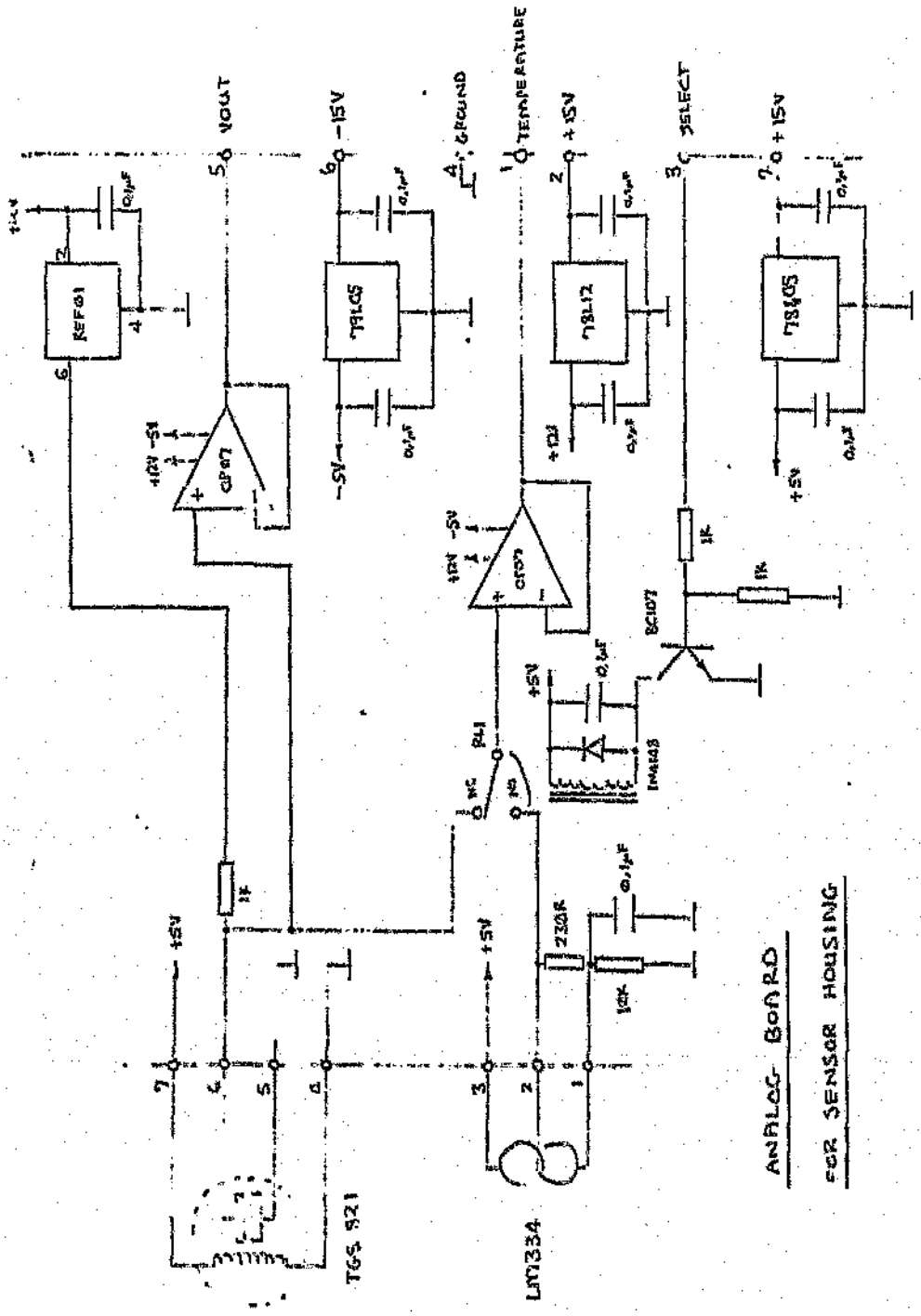


Figure 7.1 Circuit diagram of the A/D board


VOUT
-15V
GROUND
TEMPERATURE
+15V
SELECT
+15V
REF01
7805
7812
7805
CP07
CP07
BC107
1K
1K
+5V
-5V
+12V
+5V
+5V
+5

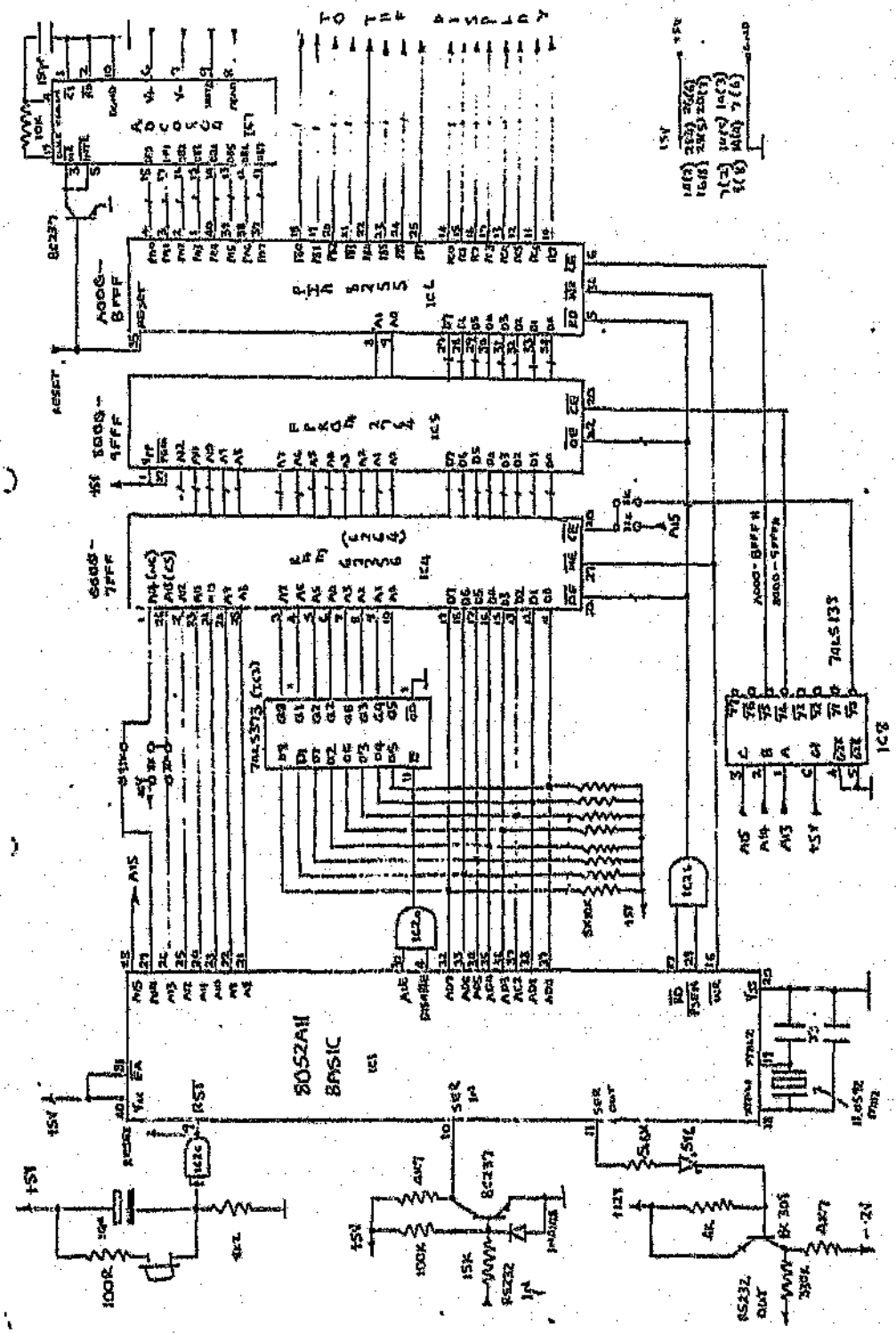


Figure 7.3 Circuit diagram of the designed datalogger

The data are stored in the RAM for later retrieval. The software was not developed further than this. It was at this stage that it was decided to use a commercial datalogger to complete the experiments.

7.2 Description of Fluke datalogger used

The Fluke datalogger is basically a multimeter with a printer attached. The datalogger can be programmed to scan a number of user selectable channels. Each channel can be programmed for a different voltage or current range. Each channel also has two alarm settings associated with it. Each channel is scanned, and then printed out with the corresponding time and date. The scan rate is user selectable.

The datalogger proved very useful, allowing a number of the experiments to be completed. One advantage of the datalogger is that it is based on old technology. Therefore the datalogger was not used that often by ESKOM. This allowed my use of the instrument to be unrestricted.

8 RECOMMENDATIONS

A number of recommendations can be made from the experience gained in constructing and using the experimental apparatus.

All of the apparatus used for the experiments can be successfully used for future experiments. This is especially true for the experimental tank and the gas-tight chamber. The design for the datalogger can be used for other projects as well.

8.1 Recommendations for use of Experimental tank

The tank requires very little modifications for future experiments. It provides a ideal vessel for testing on-line monitors, either by injecting hydrogen gas, or generating partial discharge or arcing in the oil. The one useful addition would be adding valves independently from the ports for oil samples. This would be more flexible, because an on-line monitor can be used on a port, and an oil sample can be taken at the same height without modification to the on-line monitor.

8.2 Recommendations for the on-line monitor

The on-line monitor is based on a similar principle to the Hydran monitor. A membrane is used to allow the dissolved hydrogen gas in the oil to diffuse through into a gas chamber. This concentration is detected by a hydrogen sensor. The diffusion is very dependent on temperature. I believe that this is one of the main problems with this type of on-line monitor. The only reliable method is to draw out a certain volume of oil. This must be degassed, and then the concentration of hydrogen gas from this measured. Due to the cost and complexity, this will preclude it's usage on CTs, but will be very useful for HV transformers.

8.3 Recommendations for the gas-chamber

This chamber will prove useful for calibrating the hydrogen sensors, and the on-line monitors. The one improvement would be some method of mixing the hydrogen gas and the oil better. This could be fan driven by an external motor. The problem with this is to get a gas-tight seal for the spindle. Alternately a fan attached to a magnet assembly that can be driven by a magnetic stirrer.

8.4 Recommendations for the Hydran monitor

The Hydran has been successfully used in ESKOM for detecting problems with HV transformers. But the problem of temperature dependence remains. The exact cause for the temperature variations should be ascertained, ie. is it the temperature influence on the rate of diffusion of the hydrogen gas through the membrane, or is it the hydrogen concentration in the transformer that is changing. I believe from the experiments done on the Hydran, that it is temperature change on the diffusion that is the predominant effect. This can checked reliably by using an on-line monitor not based on using a membrane to separate the dissolved gas and the oil.

8.5 Recommendations for the hydrogen sensors

Each sensor has its own advantages and disadvantages. The Sieger sensor is definitely the one to use for accurate applications, where cost is not that important. The Figaro is suitable for a cheap and simple alarm type application with careful electronic design.

8.6 Recommendations for the datalogger

The design as it is can be used for any datalogging applications. The software written forms the basis for any datalogging application.

9 REFERENCES

1 Syprotec, Hydran 201R Incipient Fault Monitor NEMA-4 Manuel, March 1989.

2 Watson J., Yates R. A., A solid-state gas sensor, Electronic Engineering, May 1985, 47 - 57.

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1 INTRODUCTION AND HISTORY

Appendix C has been written as a self-contained document. A description of each experiment is given. A description of the method used to perform the experiment, a description of the apparatus, and results are given. This is followed by the conclusions that can be drawn from the results for that experiment, and the recommendations for further work or improvement in the experimental procedure.

Finally, the overall conclusions and recommendations that can be drawn from the results of all the experiments are given.

To give the reader a better overall view of the project, the history background to the experiments is given.

The overall aim of the project was to build a low cost gas-in-oil on-line monitor, and use that to test the response of a monitor mounted at various heights on a mock-up of a CT (Current transformer) - the experimental tank.

Two different hydrogen sensors were obtained, namely the Sieger sensor and the Figaro sensor. The Sieger sensor is based on a fuel cell, while the Figaro sensor uses an resistant element. To test the response of these sensors, they were mounted in the air space of the experimental tank. This formed the basis of Experiment 1. Because of the rapid response from both sensors to arcing produced in the bottom of the tank, a large number of tests were conducted to investigate this more fully. This also allowed more data to be available to compare the sensors. The Sieger is an expensive pre-calibrated device, while the Figaro is cheaper and uncalibrated. The Figaro was the natural choice for a low cost monitor. Therefore the data were used to calibrate the Figaro sensor, with the Sieger as reference, assuming that the Sieger sensor was accurate. (Later more precise comparisons were made.)

Also while these tests were performed, oil samples were taken from the bottom of the experimental tank. This was supposed to allow a comparison between the hydrogen gas dissolved in the oil in the bottom of the tank, and the hydrogen gas in the air space. But this test hinted at the difficulty of taking reliable oil samples for GIO analysis for hydrogen gas. From a theoretical analysis, the concentrations should be proportional, this was not the case. It was supposed that the problem lay with the sampling technique. If an air bubble got into the sample tin, the hydrogen gas diffused from the oil into the air bubble, which was subsequently lost when the tin was opened. Due to the cost of the GIO analysis, it was decided to obtain two gas tight syringes to sample the oil accurately to prevent repeating the experiment.

While these syringes were on order from America, the on-line monitor was completed. This was tested on the experimental tank. These tests formed experiment 2. Arcing was produced in the bottom of the tank. The monitor was bolted to the top port which was covered by oil. The Sieger was bolted to the top of the tank, in the air space, to confirm the presence of hydrogen. No change in output from the on-line monitor occurred over a period of a day or two, even though the Sieger clearly indicated that hydrogen gas was produced. This could result only from either the monitor not working correctly, or that no hydrogen gas dissolved in the oil reaching the monitor. To test the latter supposition, a commercial unit was borrowed - the Hydran. This unit had been successfully used around the world and in ESKOM. No overall change in the output was noted. (The Hydran displayed on average a reading of 50 ppm.) To make sure that hydrogen gas was dissolving in the oil, the tank was totally filled with oil. (The Sieger sensor was removed.) At this point it was noted that the Sieger sensor was malfunctioning. (At a later stage it was ascertained that the sensor was poisoned from being over-exposed to hydrogen gas.) Again no overall increase in the output from the on-line monitor occurred to indicate an increase in the hydrogen level.

On the other hand, the output from the Hydran seemly varied with temperature. Due to this variation with temperature, the Hydran reading was regarded with doubt. The only way to check what actually was happening in the tank was to take reliable oil samples at the various ports.

In experiment 1, the Figaro sensor was calibrated to the Sieger sensors. The manufacturer guaranteed an accuracy of approximately 5 %. This was confirmed by NUCOR - S.Africa's largest consumer of the Sieger sensors. Unfortunately the Sieger sensor was poisoned, and this could not be confirmed.
To check the consistency between the different Figaro sensors, two more sensors were ordered.
While waiting for the syringes, a small gas-tight chamber was built to accurately calibrate the Figaro sensors, and the Sieger sensor. Seven tests were done on the Figaro sensors. (experiment 3)
Due to cost and time constraints, a new Sieger sensor could not be obtained. The suppliers, though, kindly replaced the sensor element with a second-hand spare that they had. Unfortunately this could not be calibrated in S.Africa. This sensor with the Figaro sensors, was calibrated in the gas-tight calibration chamber. (experiment 5)

During the period that the Sieger sensor was being repaired, a Hydran monitor was available at E.I. for calibration. An adapter was made to allow the Hydran monitor to be bolted to the gas-tight calibration chamber. A number of tests were performed on the Hydran, which are listed in experiment 4. Unfortunately the Hydran had be returned before more extensive tests could be completed.

Once the Sieger sensor was returned, the Sieger sensor was calibrated with the 3 Figaro sensors, using the calibration chamber. The results are presented in experiment 5.

For the final set of experiments, it was decided to adapt the experimental tank, so that oil samples could be taken at the various ports. Port adapters were manufactured that allowed the gas-tight syringes to take oil samples via a needle. This also allowed calibration standard hydrogen gas to be injected in the bottom of the tank. This eliminated another unknown - the total amount of hydrogen gas in the tank. The Sieger sensor allows the total amount of hydrogen gas in the air space to be ascertained. Unfortunately while the system allowed hydrogen gas to be injected in the tank successfully, the oil samples could not be taken successfully. The needle's internal diameter was too small for the oil to be drawn. This resulted in a large negative pressure on the oil drawn, which effectively degassed the oil. The easiest solution was to use the Hydran. The Hydran has a sampling valve that can directly interface to the syringe. Negotiations were entered in to borrow a Hydran from ROTEK. After numerous promises, an unit was supposed to be delivered, but withdrawn when a fault occurred on a transformer that had to monitored. It was decided again to make other adaptations that allowed the syringes to draw an oil sample directly from the ports. The syringes are screwed on the ports via small taps. The results indicated that the dissolved hydrogen gas in the oil was not reaching the ends of the ports. Again the port plugs were modified. Small pipes to the middle of the tank allowed the oil to be sampled directly from the middle of the tank at the various heights. These results are listed in experiment 6.

2 EXPERIMENT 1

2.1 Title

Time response and comparison between Sieger and Figaro hydrogen sensors in air space above the oil in the experimental CT container.

2.2 Purpose

1. To check the time response of the Sieger and the Figaro hydrogen sensors mounted in the air space above the oil when arcing occurs in the oil.

2. To provide a comparison between the Sieger, an expensive pre-calibrated self-contained hydrogen sensor (fuel cell type sensor), to the Figaro (resistant element type sensor), a cheap uncalibrated hydrogen sensor.

3. To calibrate the Figaro sensor, using the Sieger sensor as a reference, assuming that the Sieger sensor is accurate.

   (Note : The Figaro sensor is calibrated more accurately in later experiments.)

4. To compare the concentration of hydrogen gas dissolved in the oil at the bottom of the tank to the hydrogen concentration in the air space as measured by the Sieger in the air space above the oil.

5. To check whether the hydrogen gas concentration in the air space is proportional to the time length of arcing in the oil.

2.3 Apparatus

1. Experimental CT tank.

2. Sieger sensor. (Has a built in 4-20 mA loop)

3. Figaro sensor in specially built on-line monitor housing. Electronics convert the output to a 0-20 mA loop.

4. Fluke datalogger for recording of results from the two sensors onto printed paper.

5. Partial discharge measuring instrument.

6. Spark gap.

7. A 0 - 50kV supply.

8. Standard 15V power supply to power the sensors.

9. Sample vessels for oil samples.

2.4 Method

The spark gap is positioned right in the bottom of the tank. This allows a greater chance for the hydrogen to mix in the oil. Also, this provides a worst case for measuring the time response, of the hydrogen concentration in the air space above the oil. The spark gap is connected to a 0 - 50kV power supply. A partial discharge monitor is also connected to this.

The Sieger sensor is bolted to the underside of the tank's top lid. The Figaro sensor is contained inside the purpose built monitor housing. This is bolted to the top port on the experimental CT tank. The CT tank is filled to 3/4 of its height with oil. This allows the top port to be part of the air space above the . The CT tank is sealed off to the outside air. The current outputs of the sensors are connected across resistors to convert the output to a voltage that can be read by the datalogger. The sensors are supplied by a standard 15V power supply.

The datalogger is typically programmed t. read the sensors every 30 to 60 seconds for the first hour, and then every hour thereafter. The sensor readings are

printed onto a paper strip as two voltages and a date and time stamp. The Sieger output is printed as 2 to 10V output which represents a 0 to 1000 ppm hydrogen concentration. According to the manufacturer this is accurate to within 5%. The Figaro output is printed as a 0 to 10V reading inversely proportional to the hydrogen concentration.

The 0 to 50kV power supply is increased until arcing is observed on the Partial Discharge Monitor. The arcing is then maintained for 20 to 60 seconds. The 0 to 50 kV power supply is then switched off and the datalogger is started.

2.5 Results

15 tests were done over a period of two months. The data has been tabled as the voltage readings from the two sensors versus time.

The data has been converted into four sets of tables. Each table uses data from one or more particular tests done. From these tables, graphs have been generated that summarise useful information. The tables are listed below with an explanatory caption, and the graphs that have been generated :

Table 2.1 - Table of Sieger and Figaro sensor readings versus time. This table consists of tests 1,3,4,5,6,7,8 and 12. The other tests have been excluded due to the lack of enough data points. The following graphs have been generated:

Figure 2.1 - Some tests of the Sieger sensor readings versus time. This graph gives the time response of the Sieger sensor. This graph uses the results from test 1,4,5,6,7 and 12.
Figure 2.2 - Some tests of the Figaro sensor readings versus time. This graph gives the time response of the Figaro sensor. This graph uses the results from test 1,4,5,7 and 12.

SIEGER AND FIGARO SENSOR READINGS VERSUS TIME

TIME	TEST 1		TEST 3		TEST 4		TEST 5		TEST 6		TEST 7		TEST 8		TEST 12	
(minutes)	Sieger (volts)	Figaro (volts)	Sieger (volts)	Figaro (volts)	Sieger (volts)	Figaro (volts)	Sieger (volts)	Figaro (volts)	Sieger (volts)	Figaro (volts)	Sieger (volts)	Figaro (volts)	Sieger (volts)	Figaro (volts)	Sieger (volts)	Figaro (volts)
0	3.55	7.95	2.48	9.49	2	9.8	3.6	7.7	3.4	8.6	4.6	5.9	8	1	2.1	9.7
0.5	3.55				2.7	9.6	5	7.7	3.8	8.6	5.5	5.9	8	1	3.3	9.6
1	3.55				3.3	9.7	5.4	7.5	3.8	8.6	7.3	5.9	8.4	1	4.1	9.5
1.5	3.55				3.6	9.5	5.4	7.2	4	8.5	7.4	5.6	8.4	1		
2	3.55				4.1	9.2	5.5	6.9	4	8.4	7.2	5	8.7	1	4.2	9.3
2.5	3.55				4.6	8.7	5.6	6.6	4	8.3	7	4.4	8.8	0.9	4.4	8.8
3	3.55		7.3	6.3			5.8	6.3	4.1	8.1	7.1	3.8	8.8	0.9	4.7	8.5
3.5	3.55				5.3	8			4.2	8	7.3	3.4	8.8	0.8	4.9	8.2
4	3.55				5.5	7.5	6.2	5.5	4.3	7.9	7.5	3.1	8.8	0.8	5	7.6
4.5	3.55				5.8	7.2	6.2	5.1	4.4	7.7	7.8	2.7	8.8	0.8	5.2	7.6
5	3.55	7.95	8.26	3.19			6.5	4.7	4.4	7.6	7.8	2.5	8.8	0.7	5.3	7.3
5.5					6.6	6.5	6.4	4.4	4.4	7.4	7.8	2.2	8.8	0.7	5.4	7
6	3.6	7.9	8.42	2.44	6.5	6.2	6.6	4.1	4.4	7.3	7.7	2	8.8	0.7	5.5	6.7
6.5					6.4	5.9	6.6	3.7	4.5	7.2	7.7	1.8	8.8	0.7	5.6	6.4
7	3.73	7.81	8.51	1.95	6.4	5.6	6.6	3.5	4.5	7.1	7.7	1.7			5.6	6.2
7.5					6.5	5.3			4.6	6.9	7.8	1.6			5.7	5.9
8	3.9	7.65	8.56	1.64	6.6	5	6.7	3.1	4.6	6.8	7.8	1.5	8.8	0.6	5.7	5.7
8.5					6.7	4.8			4.6	6.7	7.8	1.4				
9	4.05	7.46	8.59	1.45	6.8	4.5	6.8	2.8	4.6	6.6	7.8	1.4			5.8	5.3
10	4.25	7.24	8.61	1.31	6.9	4.1	6.9	2.5	4.7	6.4	7.9	1.3	8.8	0.5	5.9	5
11	4.4	6.99	8.63	1.24	6.9	3.8	6.9	2.3	4.7	6.3					6	4.7
12	4.55	6.73	8.64	1.18	7	3.5	7	2.2	4.7	6.2						
13	4.65	5.51	8.65	1.14	7	3.3	7	2.1			8	1.1				
14	4.75	6.33			7.1	3.2	7.1	2	4.8	5.6						
15	4.9	6.15	8.66	1.08	7.1	3	7.1	1.9							6.1	3.9
16	5	5.97			7.1	2.9	7.1	1.9								
17	5.05	5.83			7.1	2.9										
18	5.15	5.71	8.67	1.05	7.1	2.8										
19	5.2	5.61			7.1	2.7										
20	5.25	5.52			7.1	2.7	7.1	1.7	4.9	5.5	8	1	8.8	0.5	6.2	3.6
21	5.3				7.2	2.6										
22	5.35	5.34			7.2	2.6										
23	5.4	5.26			7.2	2.4										
24	5.4				7.2	2.6										
25	5.4	5.16			7.2	2.5	7.1	1.7	4.9	5.5	8	1			6.2	3.3
26	5.43	5			7.2	2.5										
27	5.45				7.2	2.5										
28	5.45				7.2	2.4										
29	5.45				7.2	2.4										
30	5.5				7.2	2.4	7.2	1.7	4.9	5.4	8	0.9	8.8	0.5	6.2	3.2
35	5.5				7.1	2.4	7.1	1.6	4.9	5.4					6.1	3.1
40	5.5	4.9					7.1	1.6	4.8	5.4			8.8	0.5		
45	5.45						7.1	1.6					8.8	0.5		
50	5.45						7.1	1.6								
55	5.45		8.54	0.98			7.1	1.6								
60							7.1	1.6			8	1				
65							7	1.6			8	1				
70																
75																
80																
85			8.21													
90																
120																
150																
180									4.7	5.6						
210																
240																
270																
300																
360			8.7	0.54												

Table 2.1 Sieger and Figaro sensor readings versus time for various tests

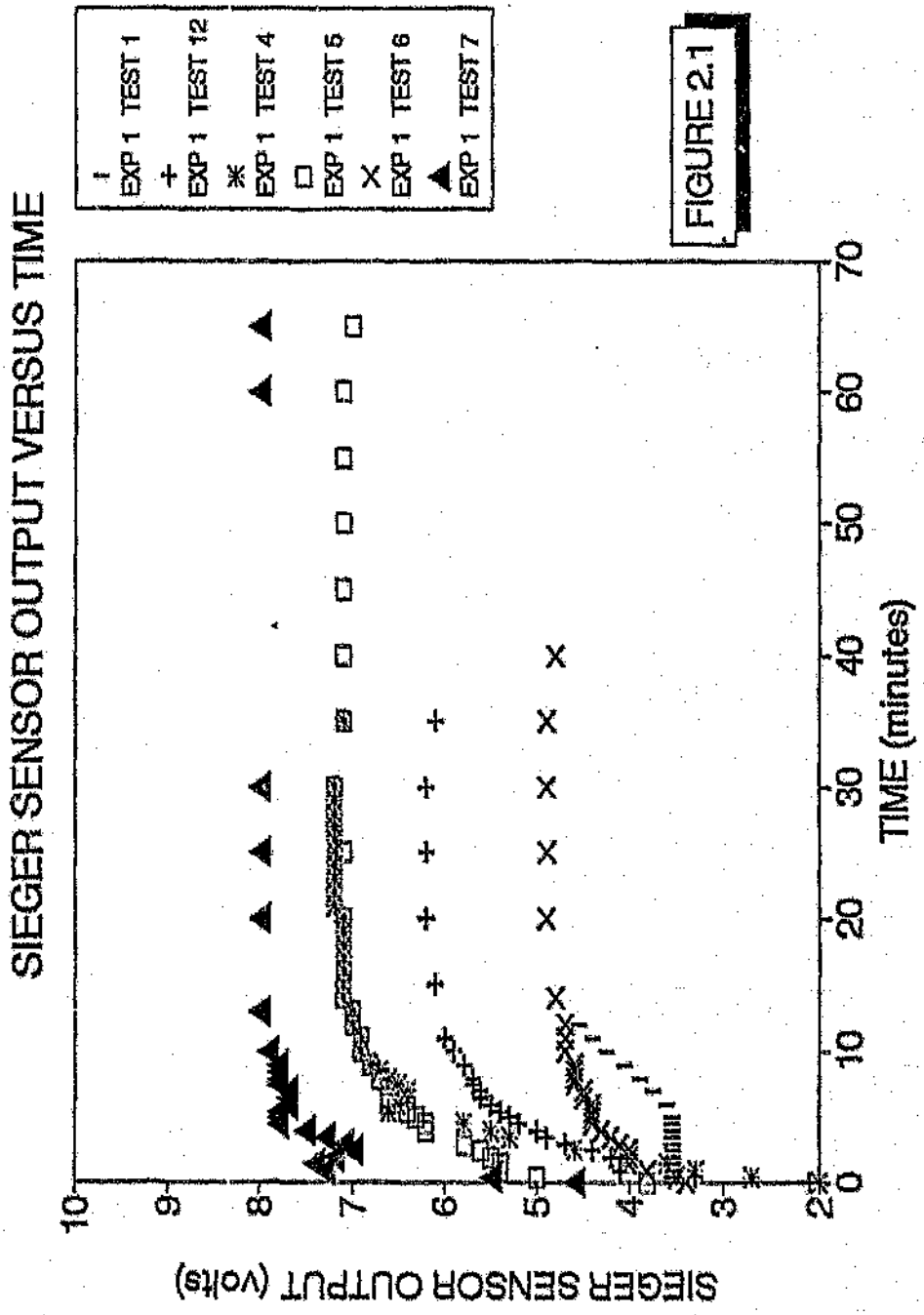


Figure 2.1 Sieger sensor readings versus time

FIGURE 2.2

Figure 2.2 Figaro sensor readings versus time

Table 2.2 - Table of the Figaro sensor readings versus the Sieger sensor readings for various tests. For all the tests, the hydrogen concentration increases gradually for approximately an hour and then drops slowly over a period of one to two days. Only the readings from the period when the hydrogen concentration is decreasing, are used to compare the two sensors, as this minimises the time response error. Only tests 4,5,11,13,14 and 15 are used, as these have enough suitable data.

Figure 2.3 - The Figaro sensor readings are compared to the Sieger sensor readings for the above mentioned tests. This graph uses data from tests 4,5,11,14 and 15.

Table 2.3 - Table of various gas concentrations in the oil at the bottom of the CT tank versus hydrogen concentration in air space. These results were obtained from GIO analysis of the oil sampled at the bottom of the tank. The hydrogen concentration in the air space was obtained from the readings of the Sieger sensor. Oil samples were taken from the bottom of the CT tank via the tap. The oil samples were taken during tests 3,4,5,6,7 and 8 of experiment 1.

Figure 2.4 - Comparison between the hydrogen and acetylene concentration in the oil at bottom of the tank, and the hydrogen concentration in the air space. The data came from tests 3,4,5,6,7 and 8.

Table 2.4 - Table of maximum readings from Sieger sensor versus length of time of arcing. This table consists of data from tests 4,5,6,7,8,13,14 and 15.

Figure 2.5 - Graph of the maximum readings from the hydrogen sensor versus length of time of arcing. Uses data from tests 4,5,6,7,8,13,14 and 15.

SIEGER (volts)	SIEGER (ppm)	TEST 4 (volts)	TEST 5 (volts)	TEST 12 (volts)	TEST 14 (volts)	TEST 15 (volts)
2	0	9.9				
2.1	12.5					
2.2	25					
2.3	37.5					
2.4	50					
2.5	5					
2.6	15					
2.7	87.5					
2.8	100					
2.9	112.5					
3	125					
3.1	137.5				9	8.9
3.2	150			9	8.9	
3.3	162.5			8.7	8.9	
3.4	175		8.1	8.4	8.8	
3.5	187.5		8.4	8.1	8.7	
3.6	200		8.3		8.6	
3.7	212.5		8		8.5	
3.8	225	7.7	7.8		8.4	
3.9	237.5	7.6	7.6		8.4	
4	250	7.4	7.5		8.1	
4.1	262.5	7.2	7.3		8	
4.2	275	7.1			7.9	
4.3	287.5				7.8	8.1
4.4	300				7.8	8.9
4.5	312.5				7.4	
4.6	325					8.7
4.7	337.5				7.3	8.2
4.8	350				7	4.6
4.9	362.5			4.7		
5	375			4.6	6.8	4.1
5.1	387.5			4	6.6	3.8
5.2	400			3.9		
5.3	412.5	5		3.6	6	3.6
5.4	425			3.4	3.4	3.3
5.5	437.5	4.5		3.3		
5.6	450			3.2	3.1	3
5.7	462.5	4		3.7		
5.8	475			2.5	4.3	2.4
5.9	487.5	3.5		2.4		
6	500			2.2	4	2.2
6.1	512.5	3.1		4.1		
6.2	525					2.1
6.3	537.5	2.7			3.8	
6.4	550					1.6
6.5	562.5				3	
6.6	575	2.5				
6.7	587.5					1.6
6.8	600	2.3			2.6	
6.9	612.5					1.3
7	625		1.6		2.2	
7.1	637.5					
7.2	650					1.1
7.3	662.5				1.8	
7.4	675					1.4
7.5	687.5					
7.6	700				1.6	
7.7	712.5					0.89
7.8	725					
7.9	737.5				1.4	
8	750			0.93		1.3
8.1	762.5			0.9		
8.2	775			0.82		
8.3	787.5			0.88	1.2	
8.4	800			0.82		1
8.5	812.5			0.8		
8.6	825			0.86	1.1	
8.7	837.5			0.87		0.75
8.8	850			0.76		
8.9	862.5					
9	875				1	0.72
9.1	887.5					
9.2	900					
9.3	912.5					
9.4	925				0.91	0.83
9.5	937.5					
9.6	950					
9.7	962.5					0.89
9.8	975				0.89	
9.9	987.5					
10	1000					
10.1						
10.2						
10.3					0.81	

Table 2.2 Figaro sensor readings versus the Sieger sensor readings for various tests

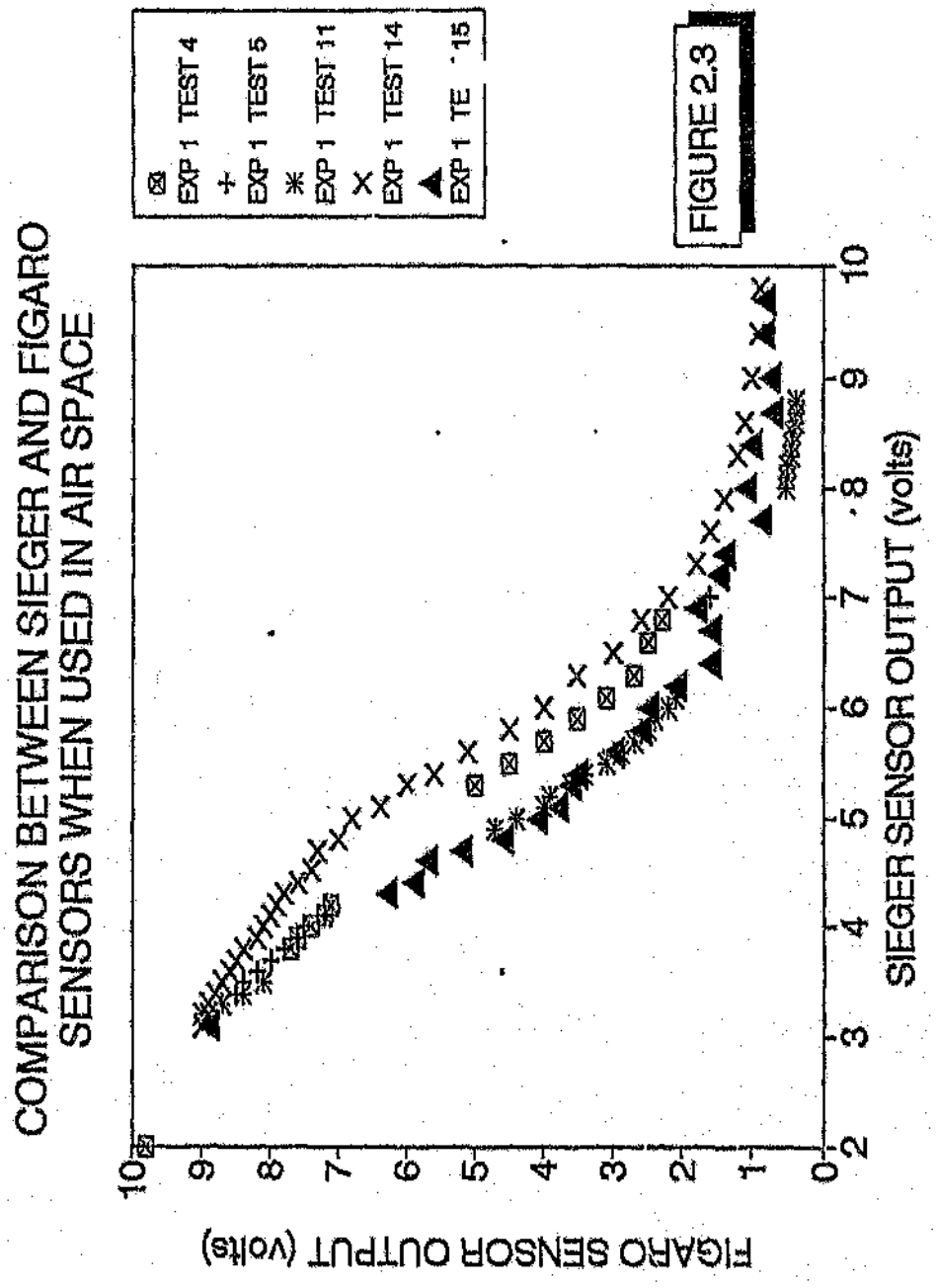


Figure 2.3 Comparison between the Sieger and the Figaro sensors

Table 2.3 Hydrogen concentration in the air space versus gas concentrations in oil

TEST	SAMPLE	SIEGER READING	LAB GAS-IN-OIL ANALYSIS FROM EI LAB								
		H2	H2	CH4	C2H4	C2H6	C2H2	CO	CO2	O2	N2
		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
3	1	60	51	1	17	1	1	20	425	26120	55160
5	1	175	8	1	9	0	3	5	200	25536	50941
5	2	175	0	1	8	0	4	6	194	23263	46781
4	2	233	16	2	12	0	3	0	105	25316	52261
6	3	335	19	2	8	0	4	13	264	23768	49932
6	4	335	16	2	9	1	5	13	231	27291	63498
5	3	470	16	1	13	0	1	11	268	26951	57850
4	1	640	7	2	10	0	0	0	109	24619	52298
7	1	750	16	2	9	1	7	13	212	24110	49464
3	2	850	13	1	17	0	6	15	311	27457	56096
8	1	1200	183	66	185	14	989	27	232	24993	51618
8	2	1200	228	79	215	16	1058	34	349	26792	54158

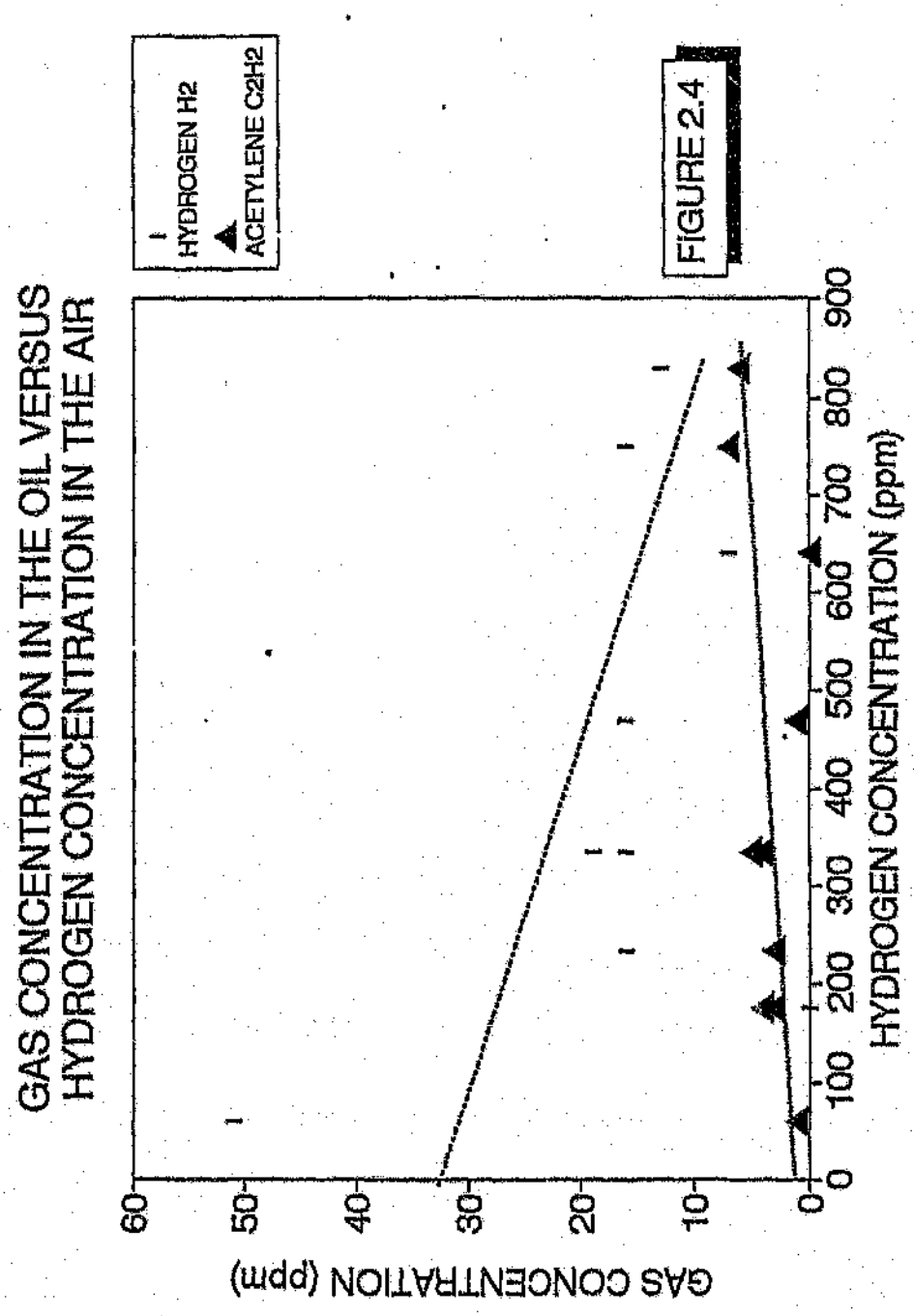


Figure 2.4 Gas concentration in the oil versus hydrogen concentration in the air

Table 2.4 Maximum readings from the Sieger sensor versus length of time of arcing

TEST	ARCING TIME (seconds)	ORIGINAL VOLTAGE (volts)	FINAL VOLTAGE (volts)	DIFFERENCE IN VOLTAGE (volts)
8	15	7.9	8.7	0.8
5	20	3.8	7.1	3.3
6	20	3.4	4.9	1.5
4	30	2	7.2	5.2
7	40	4.6	8	3.4
15	40	3.4	10.1	6.7
13	60	2.9	10.3	7.4
14	60	2.3	10.3	8

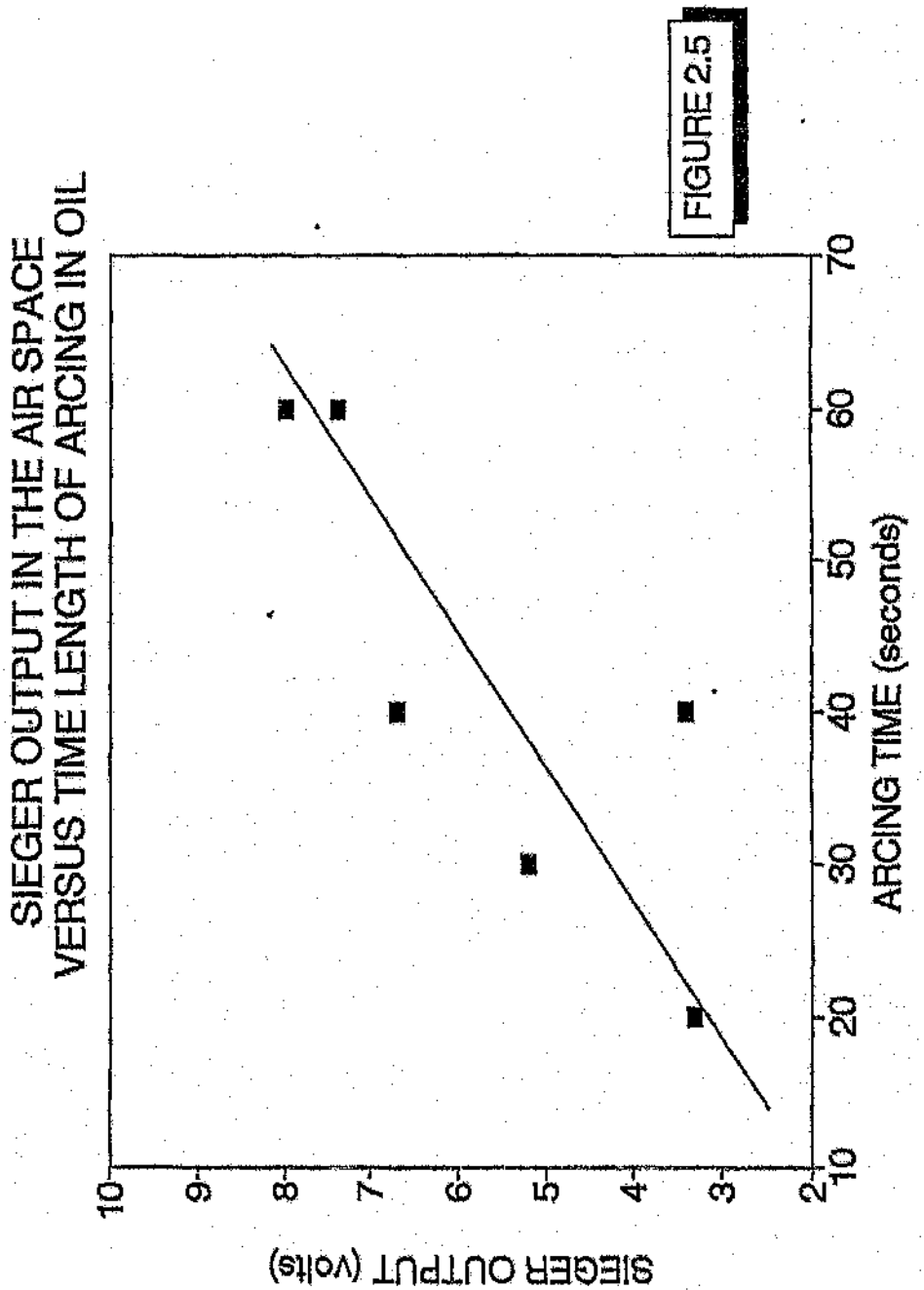


Figure 2.5 Sieger sensor reading in the air space versus time length of arcing in the oil

2.6 Conclusions

The following conclusions can be made from the results:

1. The Sieger sensor responses to a fault in the bottom of the tank within 1 minute, and reaches a steady reading within 15 minutes. (figure 2.1)
2. The Figaro sensor responses to a fault in the bottom of the tank within 2 minutes, and reaches a steady reading within 20 minutes. (figure 2.2)
3. Assuming the Sieger sensor is accurate, it can be seen from figure 2.3 that the Figaro response is not linear. There is also a spread in the reading. There is approximately a maximum of a 125ppm spread for any particular voltage reading.
3. From figure 2.4 it can be seen that the hydrogen concentration in the air space is not proportional to the hydrogen concentration in the oil, but is proportional to the acetylene concentration in the bottom of the oil. The acetylene dissolves relatively easily in the oil compared to the hydrogen. When an oil sample is taken, if the sampling tin is not perfectly sealed, the hydrogen will escape. I believe that unreliable sampling techniques account for the erratic results for hydrogen concentration in the oil.
4. From figure 2.5 it can be clearly seen that the hydrogen concentration in the air space is proportional to the duration of the fault.

2.7 Recommendations

The following recommendations can be made:

1. Mounting a sensor in the air space can be an excellent method for detecting a fault in the oil for small oil quantities. The hydrogen concentration in the air was proportional to the duration of the faults in the oil.

2. Both sensors provided good response times, the Sieger sensor being a bit faster. Assuming that the Sieger sensor is accurate and repeatable (according to the manufacturer's specifications), the Figaro sensor is not suitable for accurate measurements. More tests, independent of the Sieger sensor should be done. Note: These tests were performed in experiment 3 (Chapter 4) and experiment 5 (Chapter 6).
3. The sampling tins do not seem to provide accurate results for hydrogen gas dissolved in the oil. an accurate method should be used for future experiments. Note: Gas-tight syringes were used for future experiments.

3 EXPERIMENT 2

3.1 Title

Tests with on-line monitor and the Hydran on-line monitor.

3.2 Purpose

1. To check whether the self built on-line monitor detects any hydrogen dissolved in the oil.

2. To check whether the Hydran, a commercial unit, detects any hydrogen dissolved in the oil.

3.3 Apparatus

1. Experimental CT tank.

2. Figaro sensor in specially built on-line monitor housing. Electronics convert the output to a 0-20 mA loop.

3. Hydran on-line monitor.

4. Partial discharge measuring instrument.

5. Spark gap.

6. A 0 - 50kV supply.

7. Standard 15V power supply to power the sensors.

8. Sieger sensor

3.4 Method

The spark gap is positioned right at the bottom of the tank. This allows a greater chance for the hydrogen to mix in the oil.

The spark gap is connected to a 0 - 50kV power supply. A partial discharge monitor is also connected to this. The Sieger sensor is bolted to the bottom of the top lid of the experiment tank.

The CT tank was filled to 4/5 th's of its height with oil. The oil covered the top port. Arcing was induced in the oil and the response from the Figaro sensor noted. No significant change in output from the Figaro sensor occurred. To check that the on-line monitor was working, the Hydran was substituted.
The tank was then totally filled with oil. This would hopefully force the hydrogen gas to mix more readily with the oil. The tests were then repeated with the on-line monitor and the Hydran.

The CT tank is sealed off to the outside air. The 0 to 50kV power supply is increased until arcing is observed on the Partial Discharge Monitor. The arcing is then maintained for 1 to 2 minutes.

3.5 Results

No significant change occurred in the output from the Figaro sensor and the Hydran for the first test. The Sieger sensor indicated a hydrogen concentration in the air space greater than 1000ppm. It is suspected that the hydrogen was concentrating mainly in the air space above the oil. To test this, the transformer was filled to the top with oil. (The Sieger sensor is removed for this test.) Again no change occurred in the readings.

3.6 Conclusions

1. Either the on-line monitor and the Hydran monitor was not operating correctly, or the hydrogen in the oil was not reaching the ends of the ports. Since both monitors were not operating correctly, it was suspected that the hydrogen was not reaching the ends of the ports.

3.7 Recommendations

1. Since the on-line monitor design is based on the design of the Hydran, and is a cheaper version of it, the Hydran should be tested more fully in the laboratory. This will ascertain whether the on-line monitor will operate correctly. Note: These tests were performed, and are described in Chapter 5.
2. Accurate oil samples must be taken at the ends of the ports to ascertain whether the hydrogen dissolved in the oil is reaching the on-line monitor or the Hydran. Note: Chapter 7 describes this experiment.

4 EXPERIMENT 3

4.1 Title

Calibration of Figaro sensors.

4.2 Purpose

1. To calibrate three different Figaro sensors.
2. To the check repeatability of the Figaro sensors.
3. To compare the three Figaro sensors.

4.3 Apparatus

1. Gas-tight calibration chamber.
2. 1.0 ml gas-tight syringe.
3. Three Figaro sensors.
4. Ultra stable 5V reference.
5. Standard 5V power supply to power the sensors.
6. Fluke datalogger for recording results.
7. Calibration standard hydrogen gas.

4.4 Method

The Figaro sensors are sealed in the gas-tight calibration chamber. A standard power supply is used to power the heaters inside the sensors. An ultra stable 5V is used as a reference for the resistor element inside the sensor. The voltage developed across this resistor element is monitored by the datalogger.

Various concentrations of hydrogen gas are introduced into the chamber. The datalogger is programmed to sample the outputs from the sensors in 30 second intervals for the first half hour, and thereafter every 5 minutes.

4.5 Results

Seven tests have been conducted to date. The first four tests were for a hydrogen concentration of 500 ppm. The second three tests were for a hydrogen concentration of 100 ppm.
The results of tests 1 to 7 have been summarised in Table 4.1.
A number of graphs have been generated from this data.
Note: In test 1 the Figaro sensors were cold. For the rest of the tests the sensors were allowed to reach equilibrium temperature.

The following graphs have been generated from the test 1,2,3 and 4. The injected hydrogen quantity was 1ml. This is equivalent to a hydrogen concentration of 500ppm. These graphs show the repeatability of the three sensors.

Figure 4.1 - Readings from Figaro sensor 1.
Figure 4.2 - Readings from Figaro sensor 2.
Figure 4.3 - Readings from Figaro sensor 3.

The following graphs have been generated from tests 5,6 and 7. The injected hydrogen quantity is 0.2ml (100ppm). These graphs show the repeatability of the three sensors for this concentration of hydrogen gas.

Figure 4.4 - Readings from Figaro sensor 1.
Figure 4.5 - Readings from Figaro sensor 2.
Figure 4.6 - Readings from Figaro sensor 3.

Table 4.1 Figaro sensor readings versus time

	50PPM			50PPM			50PPM			50PPM				100PPM			100PPM			100PPM		
TIME	TEST1			TEST2			TEST3			TEST4			TIME	TEST5			TEST6			TEST7		
	Figaro1	Figaro2	Figaro3	Figaro1	Figaro2	Figaro3	Figaro1	Figaro2	Figaro3	Figaro1	Figaro2	Figaro3		Figaro1	Figaro2	Figaro3	Figaro1	Figaro2	Figaro3	Figaro1	Figaro2	Figaro3
minutes	volts	volts	volts	volts	volts	volts	volts	volts	volts	volts	volts	volts	minutes	volts	volts	volts	volts	volts	volts	volts	volts	volts
0	4.42	4.424	4.853	4.946	4.95	4.953	4.86	4.854	4.875	4.965	4.956	4.953	0	4.97	4.91	4.97	4.86	4.8	4.92	4.93	4.89	4.95
30	1.533	1.468	2.68	2.719	2.595	3.142	2.628	2.725	2.726	2.73	2.737	3.035	30	4.09	3.67	4.54	3.81	3.56	4.51	4.04	3.78	4.59
60	1.079	1.159	2.91	2.445	2.676	2.612	2.305	2.638	2.039	2.521	2.803	2.44	60	3.91	3.47	4.44	3.62	3.4	4.39	3.76	3.57	4.48
90	1.026	1.032	3.765	2.475	2.709	2.424	2.254	2.74	1.843	2.567	2.901	2.223	90	3.72	3.44	4.42	3.58	3.39	4.39	3.7	3.55	4.44
120	1.208	1.401	3.901	2.53	2.834	2.356	2.315	2.913	1.765	2.55	2.978	2.12	120	3.71	3.46	4.41	3.58	3.41	4.35	3.69	3.56	4.43
150	1.283	1.504	3.967	2.591	2.955	2.259	2.368	2.887	1.729	2.568	3.059	2.069	150	3.72	3.49	4.42	3.59	3.43	4.35	3.7	3.58	4.43
180	1.335	1.593	4.081	2.647	3.016	2.27	2.431	2.945	1.712	2.617	3.094	2.041	180	3.74	3.52	4.42	3.61	3.46	4.36	3.72	3.6	4.43
300	1.4	1.655	4.089	2.706	3.072	2.264				2.623	3.144	2.03	300	3.75	3.55	4.43	3.63	3.48	4.36	3.73	3.62	4.43
330	1.47	1.703	4.163	2.77	3.124	2.258	2.522	3.054	1.713	2.741	3.189	2.034	330	3.77	3.57	4.41	3.66	3.51	4.37	3.75	3.64	4.43
360	1.571	1.802	4.161	2.823	3.217	2.294	2.646	3.154	1.753				360	3.81	3.62	4.45	3.7	3.53	4.38	3.79	3.68	4.44
420	1.71	1.93	4.32	3.01	3.3	2.35	2.78	3.29	1.81				420	3.85	3.66	4.47	3.74	3.59	4.4	3.82	3.72	4.46
480	1.81	2.01	4.34	3.13	3.38	2.41	2.9	3.33	1.87				480	3.88	3.7	4.49	3.77	3.63	4.42	3.86	3.75	4.47
540	1.9	2.092	4.355	3.219	3.452	2.435	3.033	3.447	1.947				540	3.91	3.73	4.5	3.81	3.66	4.44	3.89	3.73	4.48
600	1.958	2.13	4.295	3.343	3.517	2.553	3.145	3.48	2.029				600	3.91	3.77	4.52	3.84	3.7	4.46	3.92	3.81	45
660	2.057	2.224	4.312	3.436	3.573	2.618	3.224	3.546	2.137				660	3.97	3.8	4.54	3.87	3.73	4.48	3.95	3.84	4.52
720	2.102	2.312	4.41	3.516	3.652	2.73	3.359	3.608	2.214				720	4	2.83	4	3.91	3.76	4.5	3.98	3.87	4.53
780	2.231	2.39	4.431	3.595	3.681	2.83	3.414	3.664	2.313				780	4.03	3.56	4 7	3.94	3.79	4.51	4	3.89	4.55
840	2.312	2.473	4.494	3.655	3.733	2.929	3.525	3.716	2.421				840	4.15	3.99	4	2.96	3.82	4.53	4.03	3.92	4.56
900	2.473	2.544	4.529				3.602	3.763	2.537				900				3.99	3.85	4.53	4.06	3.94	4.58
960							3.663	3.812	2.653				960				4.02	3.88	4.56	4.08	3.97	4.59
1020							3.719	3.854	2.773				1020				4.05	3.91	4.58	4.11	3.99	4.61
1080							3.773	3.895	2.834				1080				4.08	3.94	4.6			
1140				3.903	3.934	3.47	3.824	3.933	3.016				1140	4.26	4.1	4.69	4.1	3.96	4.61			
1200	2.767	2.857	4.669				3.869	3.968	3.151				1200				4.13	3.99	4.62			
1260							3.902	3.996	3.242				1260				4.15	4.01	4.63			
1320													1320				4.18	4.04	4.65	4.24	4.12	4.67
1380													1380				42	4.06	4.66			
1440				4.076	4.087	3.88							1440	4.36	4.2	4.73	4.22	4.08	4.67			
1500	3.024	3.09	4.723				3.949	4.029	3.347				1500				4.24	4.11	4.68	4.34	4.22	4.72
1560	3.123	3.257	4.744	4.231	4.228	4.156							1560	4.44	4.29	4.77	4.31	4.17	4.71	4.43	4.31	4.76
2100	3.528	3.459	4.747	4.37	4.306	4.348	4.31	4.166	3.758				2100	4.51	4.37	4.8				4.5	4.4	4.79
2400	3.029	3.094	4.152	4.403	4.573	4.469	4.236	4.229	4.099	4.331	4.331	4.304	2400	4.58	4.44	4.82				4.57	4.47	4.81
2700							4.339	4.37	4.302	4.432	4.414	4.442	2700	4.63	4.5	4.84				4.63	4.53	4.83
3000							4.423	4.417	4.442	4.484	4.491	4.541	3000							4.67	4.58	4.85
3300							4.476	4.513	4.542				3300							4.71	4.63	4.87
3600							4.558	4.57	4.615				3600							4.75	4.67	4.88
3900							4.609	4.619	4.67				3900							48	4.73	4.89
4200	4.759	4.748	4.778				4.654	4.662	4.713				4200							4.8	4.78	4.9
4500							4.692	4.698	4.747				4500							4.83	4.76	4.9
4800							4.726	4.731	4.775				4800							4.84	4.78	4.91
5100							4.755	4.759	4.797				5100									

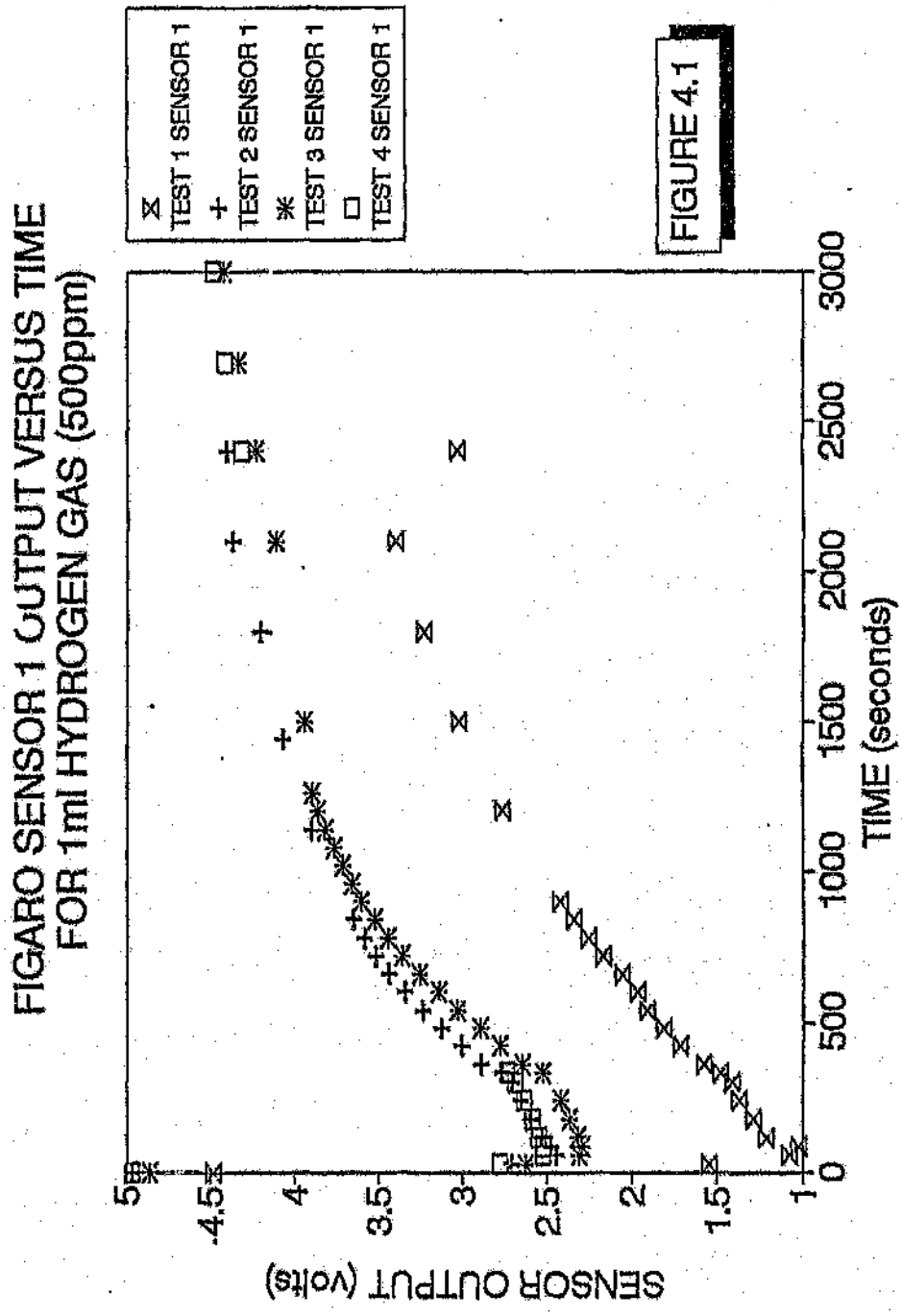


Figure 4.1 Output from Figaro sensor 1 versus time for 1ml hydrogen gas

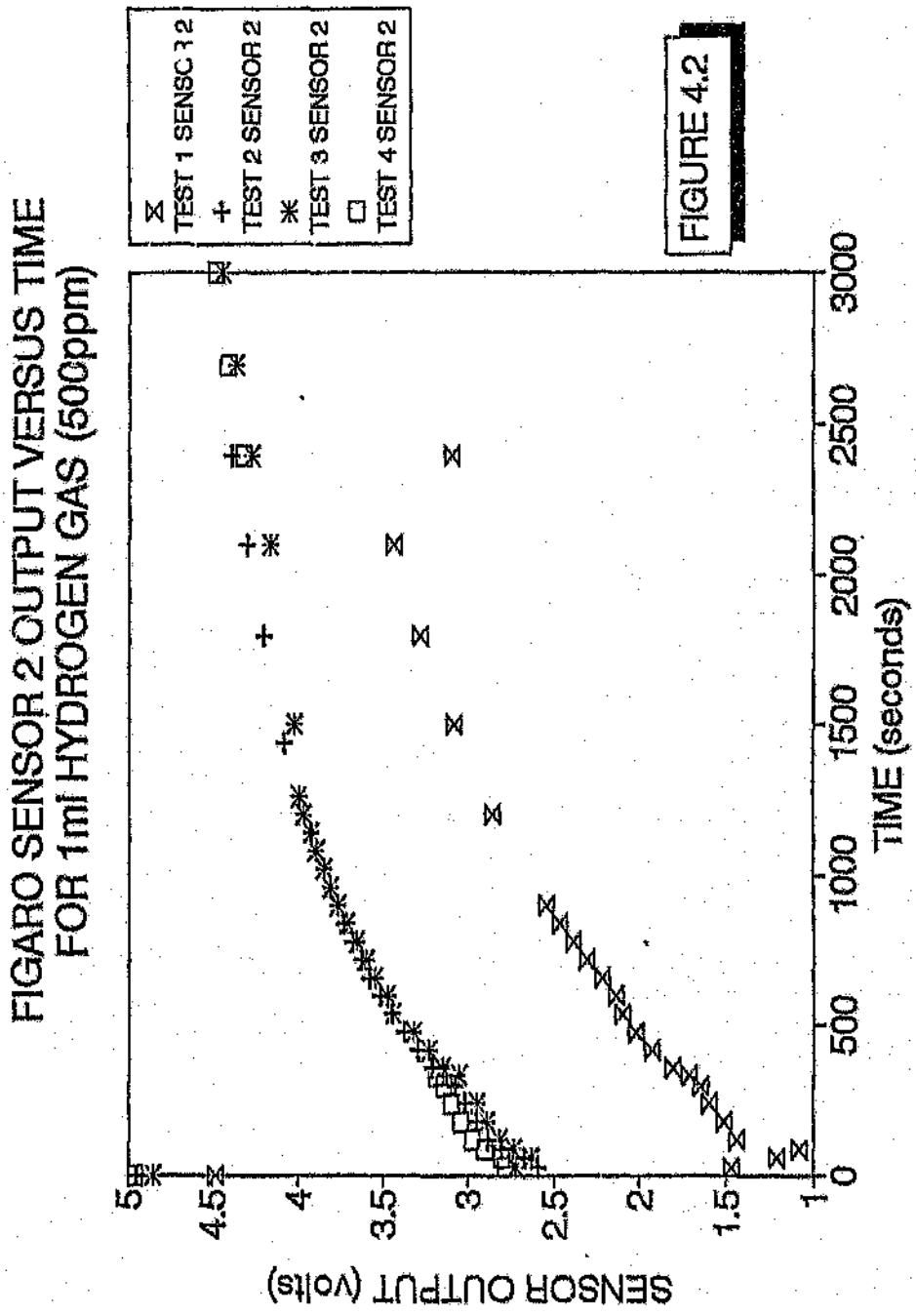


Figure 4.2 Output from Figaro sensor 2 versus time for 1ml hydrogen gas

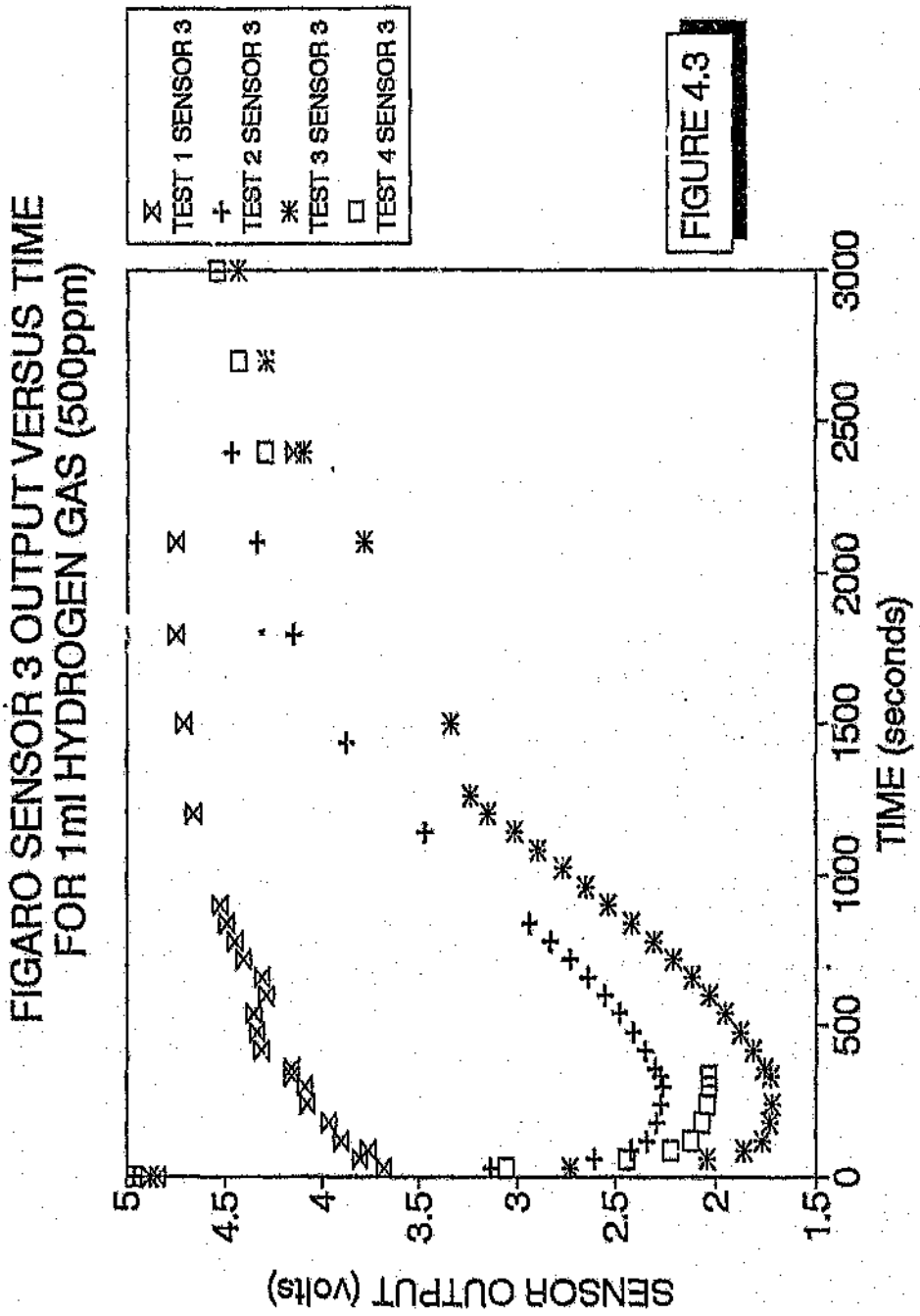


Figure 4.3 Output from Figaro sensor 3 versus time for 1ml hydrogen gas

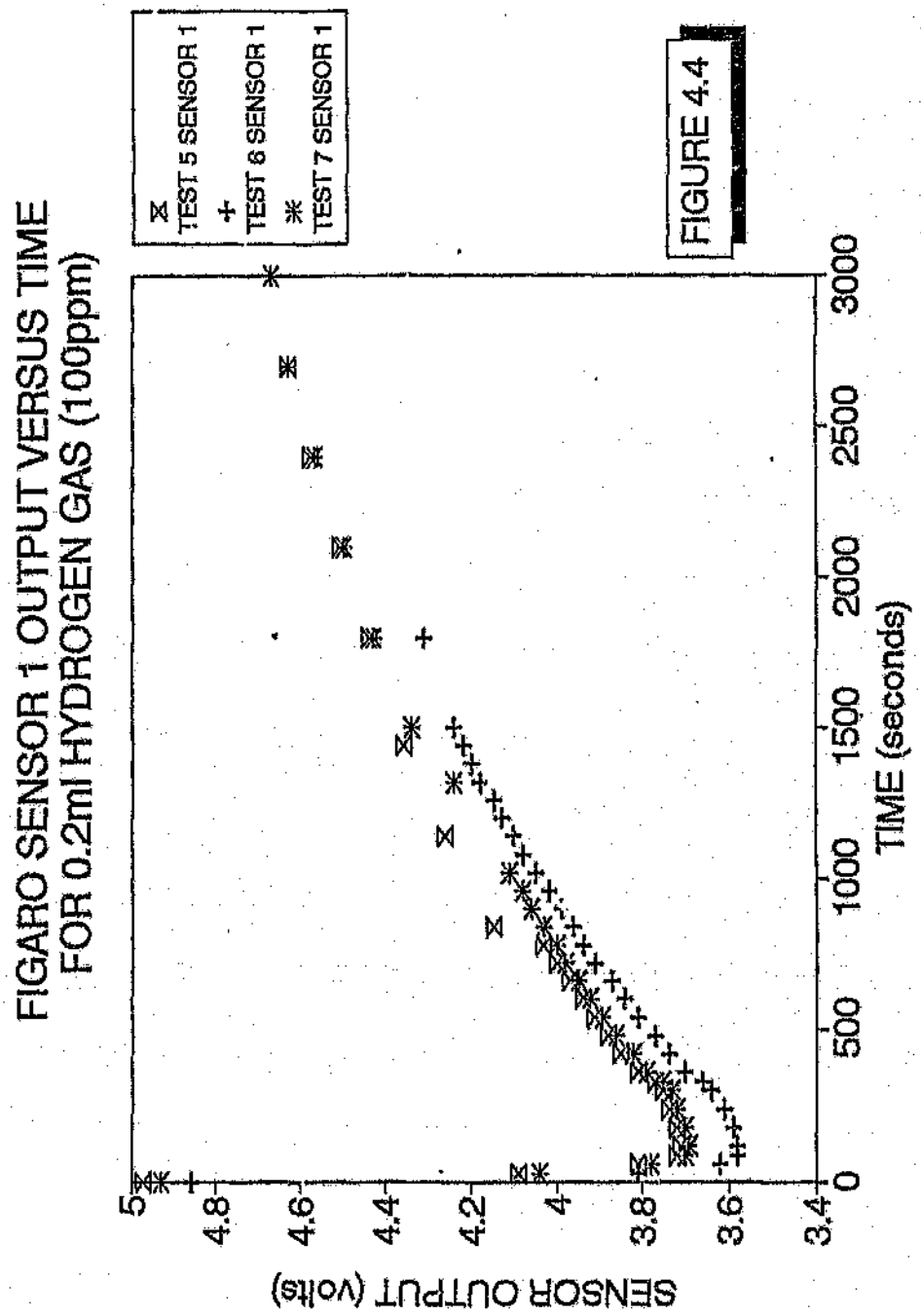


Figure 4.4 Output from Figaro sensor 1 versus time for 0.2ml hydrogen gas

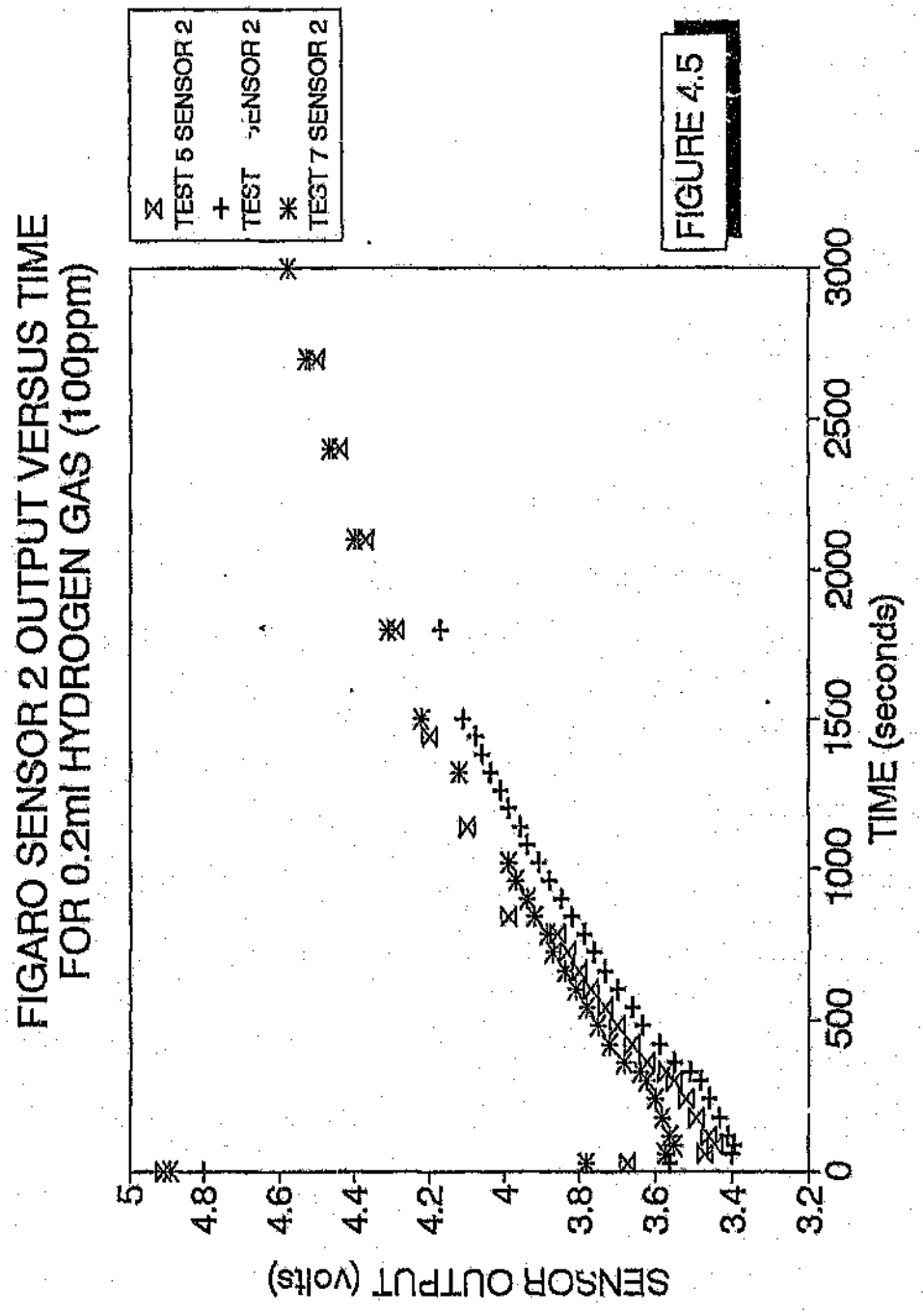


Figure 4.5 Output from Figaro sensor 2 versus time for 0.2ml hydrogen gas

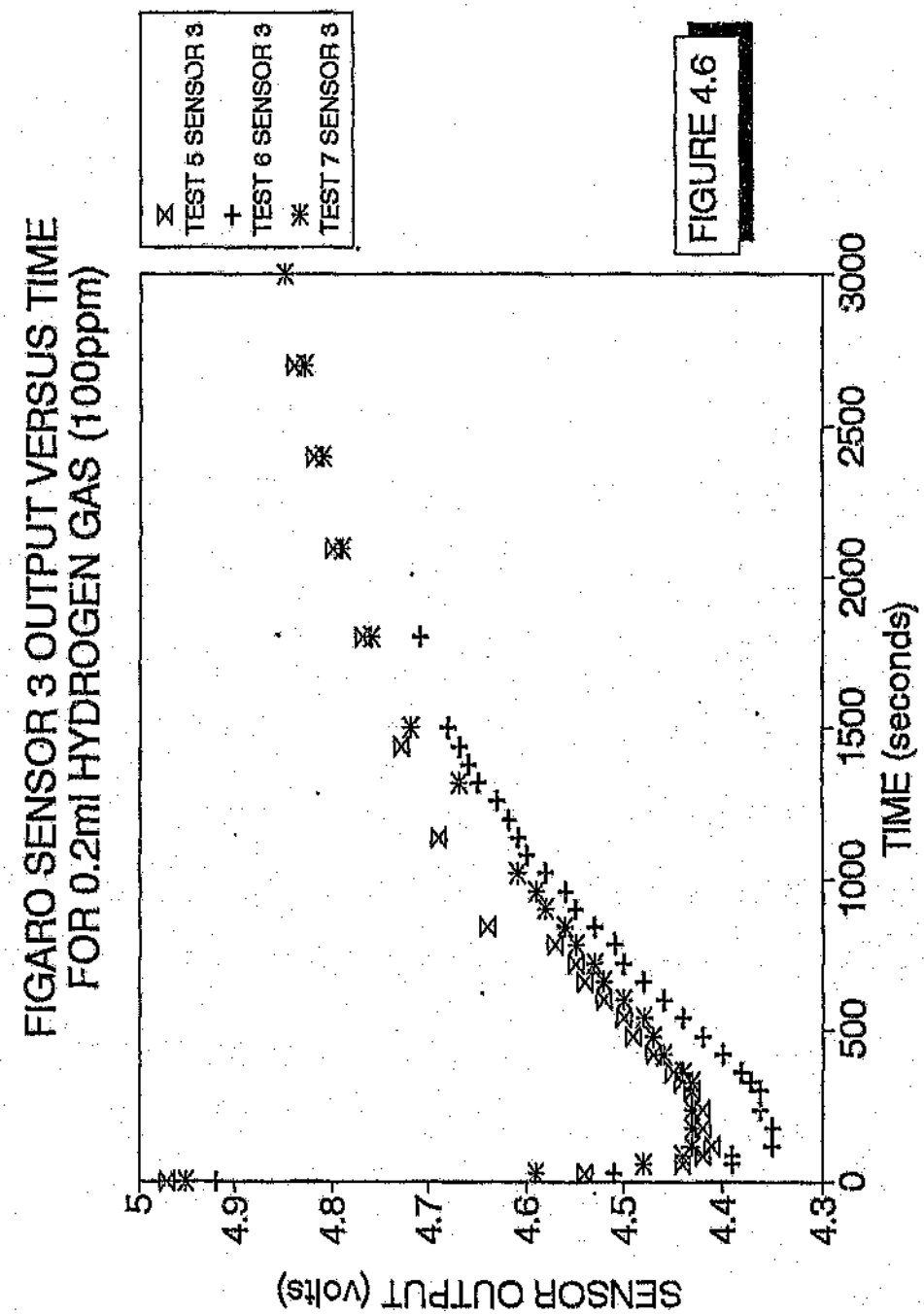


Figure 4.6 Output from Figaro sensor 3 versus time for 0.2ml hydrogen gas

The following graphs compares the 3 Figaro sensors for two tests, both for a 500 and 100 ppm concentration of hydrogen gas. These graphs show the repeatability between the different sensors.

Figure 4.7 - Comparison between the 3 Figaro sensors versus time, for a concentration of 500 ppm hydrogen gas. The data from tests 2 to 3 are used.

Figure 4.8 - Comparison between the 3 Figaro sensors versus time, for a concentration of 100 ppm hydrogen gas. The data from tests 6 and 7 are used.

The following graph shows the difference for each of the three different sensors, for different hydrogen concentrations. The data from tests 4 and 5 are used.

Figure 4.9 - Figaro outputs versus time for 500 ppm and 100 ppm hydrogen concentrations.

4.6 Conclusions

1. From figure 4.1, figure 4.2, figure 4.4 and figure 4.5 it can be seen that Figaro sensor 1 and Figaro sensor 2 have good repeatability for the first three tests. In the fourth test the readings are totally different. The sensors were cold at this stage. This implies that the sensors are accurate only if the sensors are allowed to reach an equilibrium temperature.
2. From figure 4.3 it can be seen that the repeatability of Figaro sensor 3 is poor for a 500ppm concentration of hydrogen. Sensor 1 and 2 were new sensors when the above tests were performed on them. Sensor 3 had been used approximately for a year before this. The results for figure 4.6 are better. This implies that possibly the accuracy of the Figaro sensors deteriorate as they age.

3. Figure 4.7 and figure 4.8 supports the above conclusions. The repeatability of the individual sensors are good. But the absolute readings for the Figaro sensor 3 is totally different than for the other two newer sensors. This implies that the absolute accuracy deteriorates as the sensor ages.
4. To compare the three sensors from figure 4.9, the differences in the minimum output voltage for each sensor at the two different concentrations are taken. For sensor 1 this is 1.5 volts, for sensor 2 this is 0.75 volts and for sensor 3 this is 2.3 volts. This implies that there is no consistent absolute accuracy for the sensors. This implies that the sensors will have to be individually calibrated for each application.
5. In all the results the sensor readings reached a minimum voltage after a minute or two, after which the readings slowly increased. Unfortunately it can not be ascertained whether this is part of the sensor response, or if the actual hydrogen concentration decreases.

4.7 Recommendations

1. The Figaro sensor is not suitable for accurate readings.
2. If the Figaro sensor is used, the following precautions will have be taken:
   - The readings from the Figaro sensor will be totally inaccurate for approximately a half hour after a power failure, ie. until equilibrium temperature is reached.
   - Each sensor will have be individually calibrated before use, and thereafter at least once year.
3. The Sieger sensor should be compared to the Figaro sensors to see whether the hydrogen concentration is decreasing, or if the Figaro sensor outputs change for a constant hydrogen concentration. Note: These experiments were performed, and are described in Chapter 6.

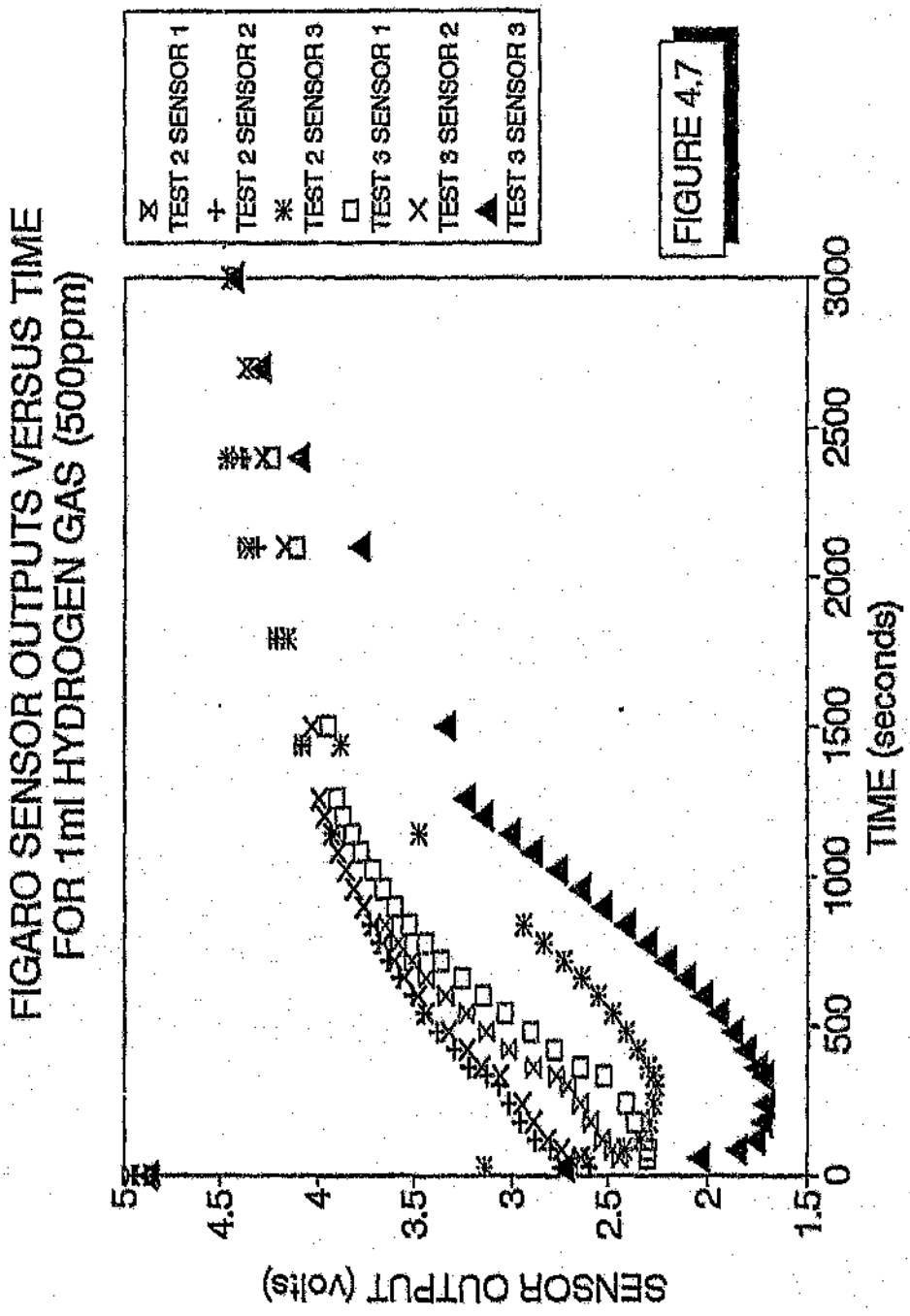


Figure 4.7 Figaro outputs versus time for 500 ppm hydrogen concentration

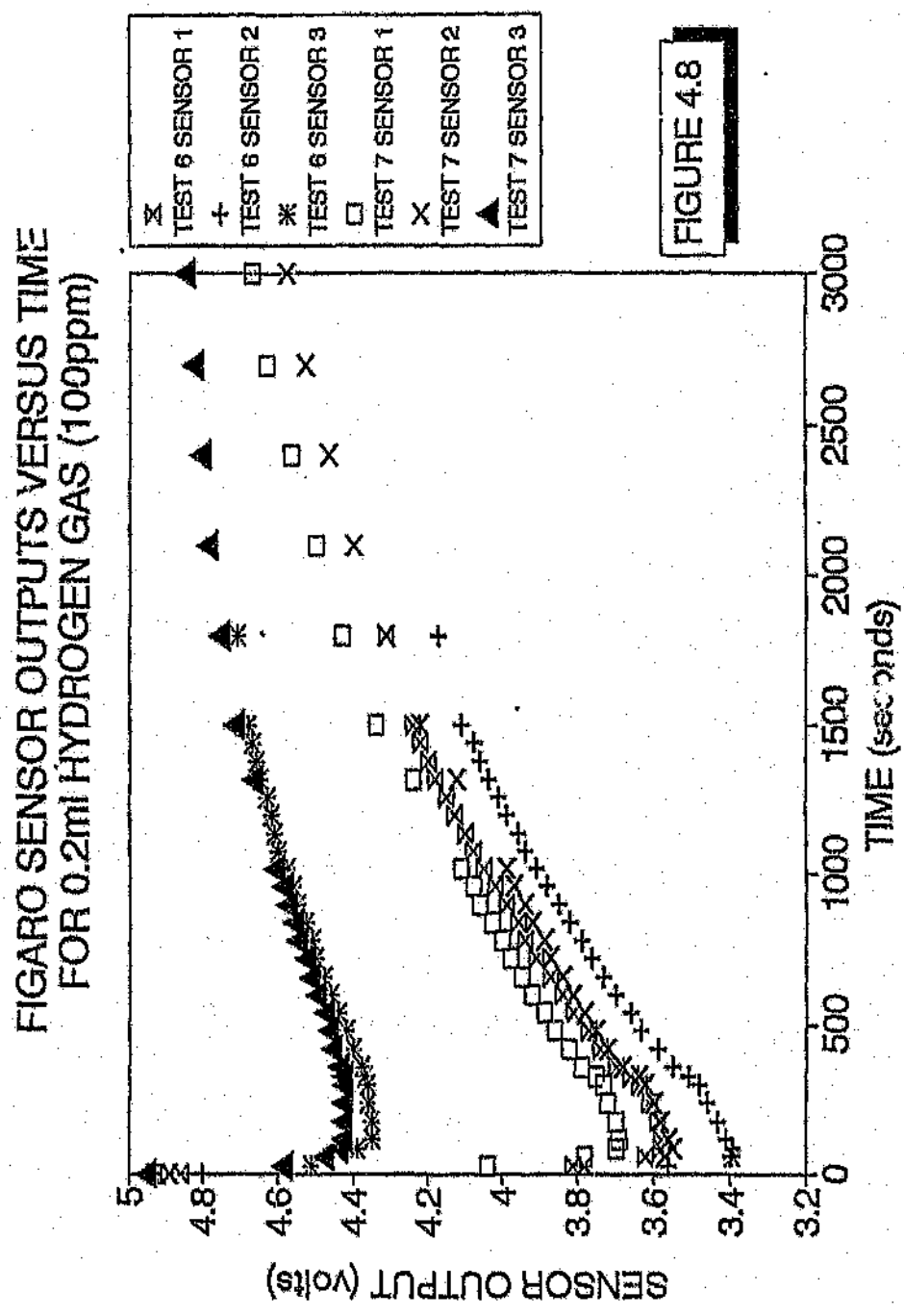


Figure 4.8 Figaro outputs versus time for 100 ppm hydrogen concentration

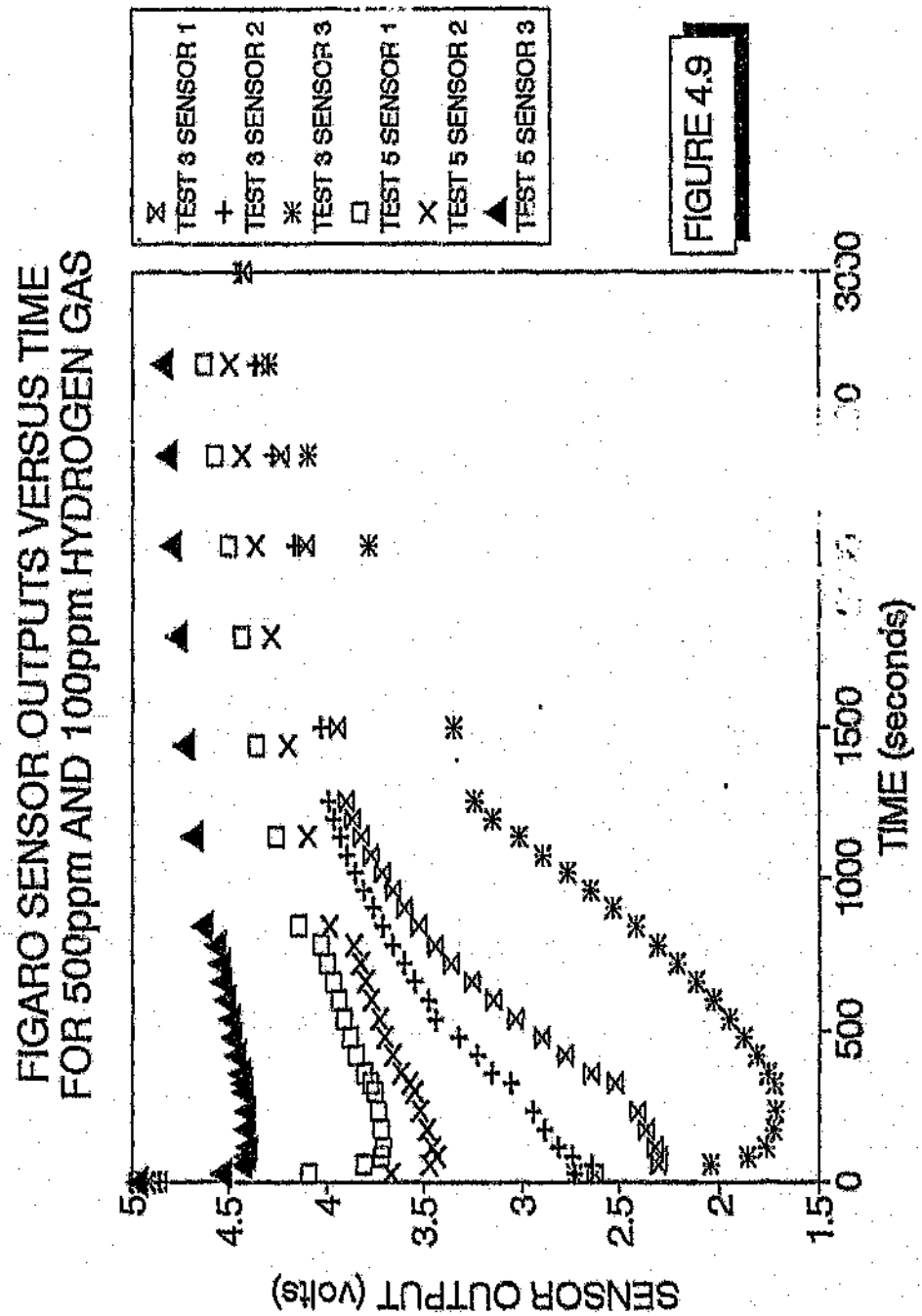


Figure 4.9 Figaro outputs versus time for 500 ppm and 100 ppm hydrogen gas

5 EXPERIMENT 4

5.1 Title

Laboratory tests on the performance of the Hydran.

5.2 Purpose

1. To check how the Hydran responds when measuring hydrogen concentration in air.

2. To check how the Hydran responds when measuring hydrogen concentration in oil.

3. To quantify the affect of air bubbles in contact with the membrane.

4. To quantify the temperature effect on the Hydran reading.

5.3 Apparatus

1. Gas-tight calibration chamber.

2. 1.0ml Gas-tight syringe.

3. Hydran on-line monitor.

4. Magnetic stirrer.

5. Calibration standard hydrogen gas.

5.4 Method

The Hydran was bolted to the gas-tight chamber. Hydrogen gas of various concentrations was introduced into the chamber. The response of the Hydran was noted at various time intervals.

For the first ten tests, no oil was present in the container. No stirrer was used for the first two tests.

A further three tests were conducted with the chamber filled with oil. A stirrer was used for these to mix the hydrogen gas and the oil. The chamber was totally filled with oil. Great lengths were gone to ensure that no air bubbles were left in the chamber that would affect the results.

In the third test, air bubbles was introduced into the chamber, and allowed to reach the membrane.

Finally the temperature effect on the Hydran reading was noted.

5.5 Results

In the first nine tests, 4.0ml hydrogen gas was injected into the gas-chamber. This is equivalent to a concentration of approximately 2000 ppm in the air. Because the Hydran has been calibrated for hydrogen gas dissolved in the oil, the Hydran should display a reading of 2000 ppm X 0.056 Ostwald Solubility Coefficient) = 112 ppm.
Figure 5.2 compares the actual readings of the Hydran to the theoretical readings for the Hydran.
In all the tests the reading rose by approximately 200ppm. This implies that the Hydran is overreading. Good repeatability was demonstrated as long as the temperature was held constant.
In the 10th test, 12.0ml hydrogen was introduced into the chamber. The Hydran reached a maximum reading of 500ppm.

In the last 3 tests, the chamber was filled with oil. First, 4.5ml (equivalent to 2200ppm) of hydrogen was injected into the chamber. Great difficulty was experienced in properly mixing the gas and the oil. The Hydran displayed its upper limit (approximately 2800ppm).

The oil was replaced and then 2.0ml hydrogen gas (1000ppm) was injected into the oil. Again the Hydran displayed 2800ppm. This was repeated. The same results occurred. After 4 hours the reading dropped to 650 ppm. When the container was shaken, so that air/hydrogen bubbles reached the membrane, the reading rose to 1355 ppm.

See **table 5.1** and **figure 5.1** for a summary of these results.
Figure 5.2 compares the actual reading of the Hydran monitor to the theoretical reading.

To test the effect of air bubbles on the Hydran reading, air bubbles were introduced at the membrane.
For 0.5ml of air introduced, the display dropped from 1300ppm to 1130ppm.
For 1.0ml of a' 'ntroduced, the display dropped from 1300ppm to 915ppm. Clearly the equilibrium conditions at the membrane are very easily upset.

The case of the Hydran sensor unit was heated up by 2 to 3 degrees Celsius. In each case the temperature rose by approximately 50 ppm.

5.6 Conclusions

1. The Hydran's repeatability is good, but the absolute accuracy was totally out, according to theoretical calculations. This implies that either this particular Hydran is inaccurate and requires proper laboratory calibration, or the Ostwald coefficient value is wrong.
2. The Hydran is very temperature sensitive.
3. The Hydran reading is sensitive to the presence of air bubbles.

Table 5.1 Hydran readings versus time for various hydrogen quantities

HYDRAN READINGS VERSUS HYDROGEN CONCENTRATION

TIME minutes	TEST 1 ppm	TEST 2 ppm	TEST 3 ppm	TEST 4 ppm	TEST 5 ppm	TEST 6 ppm	TEST 7 ppm	TEST 10 ppm
0	0	140	0	0	0	185	469	3
1						243	535	3
2			67	87	62	315		113
3			127	134	125	364	594	330
4			160	162	156	384	601	453
5			175	176	172	394	602	510
6			182	182	179	397		536
7						397		545
8			185	184	182			546
9								
10	200	357	185	184	182	397	602	546

Figure 5.1 Hydran readings versus time for various hydrogen quantities

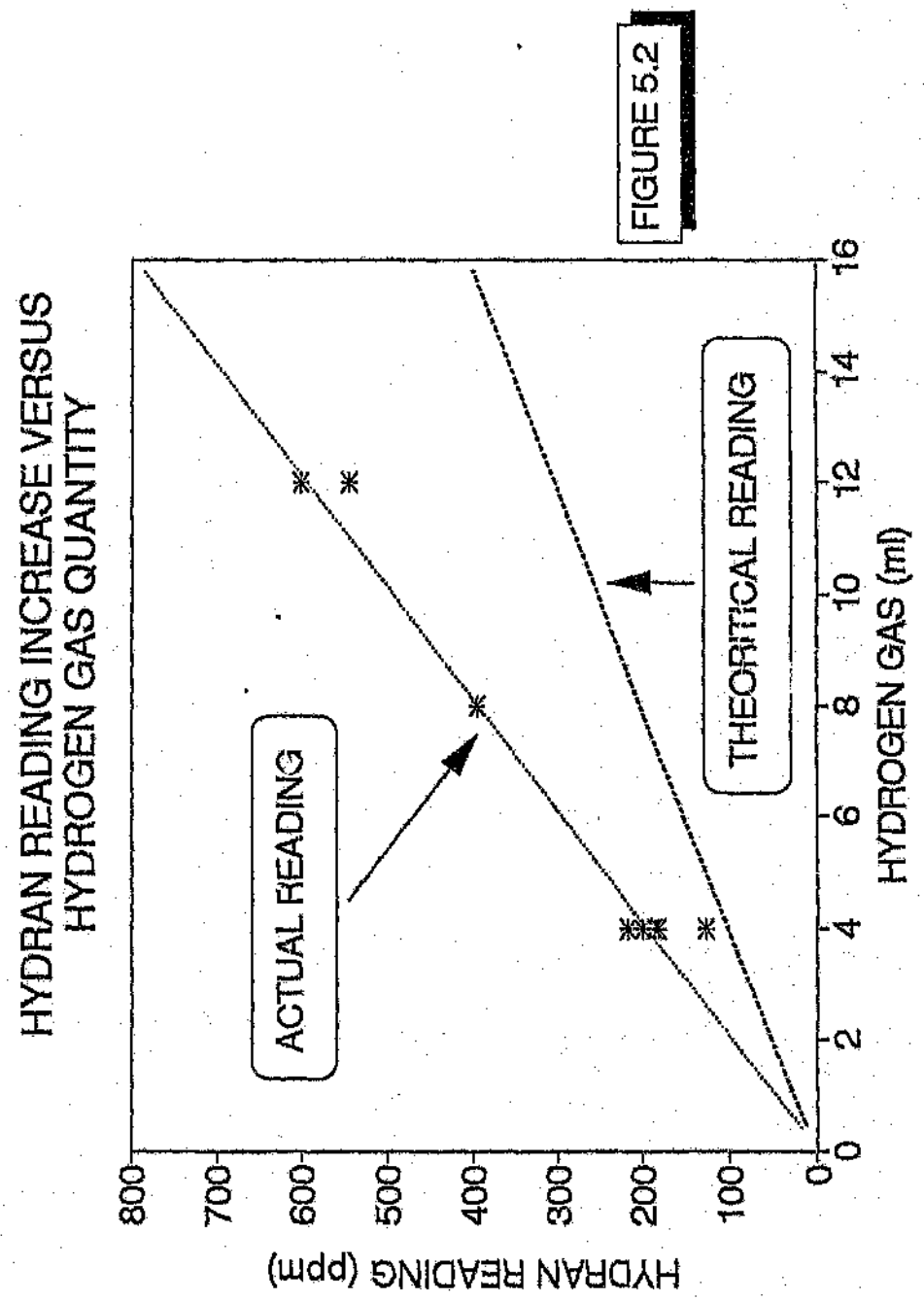


Figure 5.2 Actual and theoretical Hydran readings versus injected hydrogen quantity

5.7 Recommendations

1. A number of Hydrans should be checked to see whether the above results are consistent. This will confirm whether the absolute inaccuracy of the above Hydran is typical.
2. The actual value of the Ostwald solubility coefficient should be checked for various oils. Does this vary with age, amount of contaminants, and total gas quantity dissolved in the oil?
3. An accurate on-line monitor cannot be based on the membrane concept to separate the dissolved hydrogen from the oil.
4. A method of reliably mixing the oil and the hydrogen gas should be worked on. This will allow a more accurate assessment of the Hydran.

6 EXPERIMENT 5

6.1 Title

Calibration of Sieger and Figaro sensors using gas-tight chamber.

6.2 Purpose

1. To calibrate the Figaro sensors.
2. To compare the three different Figaro sensors.
3. To calibrate the Sieger sensor.
4. To compare the Figaro sensors to the Sieger sensor.

6.3 Apparatus

1. Gas-tight calibration chamber.
2. 1.0ml gas-tight syringe.
3. Three Figaro sensors.
4. Sieger sensor.
5. Ultra stable 5V reference.
6. Standard 5V power supply to power the sensors.
7. Fluke datalogger for recording results.
8. Calibration standard hydrogen gas.

6.4 Method

The three Figaro sensors are sealed in the gas-tight calibration chamber. The Sieger sensor is bolted to the port on the chamber. A standard power supply is used to power the heaters inside the sensors. An ultra stable 5V is used as a reference for the resistor element inside the sensor. The voltage developed across this resistor element is monitored by the datalogger. The 4-20mA output of the Sieger sensor is converted into a 2-10V signal, which is monitored by the datalogger.

Various quantities of hydrogen gas is introduced into the chamber. The gas is mixed with the air inside the chamber with a magnetic stirrer.

The datalogger is programmed to sample the outputs from the sensors in 30 second intervals for the first half hour, and thereafter every 5 minutes.

6.5 Results

The following table have been generated with its corresponding graphs:

Table 6.1 - Sieger and the 3 Figaro sensor outputs versus time for 0.5 ml injected hydrogen (equivalent to 250 ppm hydrogen concentration). The results for the separate tests are given.

Figure 6.1 - Sieger and the 3 Figaro sensors outputs versus time for 0.5 ml injected hydrogen. This figure uses the data from test 1.

	TEST 1				TEST 2			
TIME	FIG1	FIG2	FIG3	SIEG	FIG1	FIG2	FIG3	SIEG
minutes	volts	volts	volts	volts	volts	volts	volts	volts
0	5	5	5	2	5	5	5	2
30	3.6	3.7	4.3	2.2	5	5	5	2
60	3.7	3.8	4.2	3	5	5	5	2
90	3.7	3.9	4.3	3.3	5	5	5	2
120	3.8	4	4.3	3.3	3.7	3.6	4.4	2.1
150	3.8	4	4.3	3.3	3.6	3.6	4.2	3.2
180	4	4.1	4.3	3.2	3.5	3.6	4.2	3.4
210	4	4.2	4.3	3.2	3.6	3.7	4.1	3.5
240	4.1	4.2	4.3	3.1	3.6	3.7	4.1	3.5
270	4.1	4.2	4.3	3.1	3.6	3.6	4.1	3.4
300					3.7	3.6	4.1	3.4
330					3.7	3.6	4.1	3.4
360					3.7	3.6	4.1	3.4
390					3.6	3.6	4.1	3.4
420					3.6	3.6	4.1	3.3
450					3	3.2	3.6	3.4
480					3	3.3	3.4	4.2
510					3	3.3	3.3	4.6
540					3.1	3.4	3.2	4.6
570					3.1	3.5	3.1	4.6
600					3.1	3.5	3.1	4.5
630					2.9	2.6	2.4	4.8
660					2.3	2.9	2.2	5.6
690					2.3	2.9	2.1	5.7
720					2.3	3	2	5.7
750					2.3	3.1	2	5.6
780					2.3	3.2	2	5.6
810					1.8	2.5	1.8	5.6
840					1.6	2.4	0.1	6.4
870					1.6	2.5	0.1	6.7
900					1.6	2.6	0.1	6.7
930					1.6	2.6	0.09	6.6
960					1.6	2.7	0.085	6.6
990					1.1	2	0.058	6.8
1020					1.1	2	0.061	7.3
1050					1.1	1.9	0.064	7.4
1080					1.1	2.1	0.062	7.3
1110					1.1	2.1	0.054	7.3
1140					1.1	2.2	0.056	7.3
1170					1.2	2.2	0.055	7.2
1200					1.2	2.3	0.055	7.2
1230					1.2	2.4	0.056	7.1
1260					1.3	2.5	0.056	7
1320					1.3	2.6	0.058	6.9
1380					1.4	2.8	0.059	6.7
1500					1.6	3.1	0.071	6.4

Table 6.1 Sieger and the 3 Figaro sensor outputs versus time

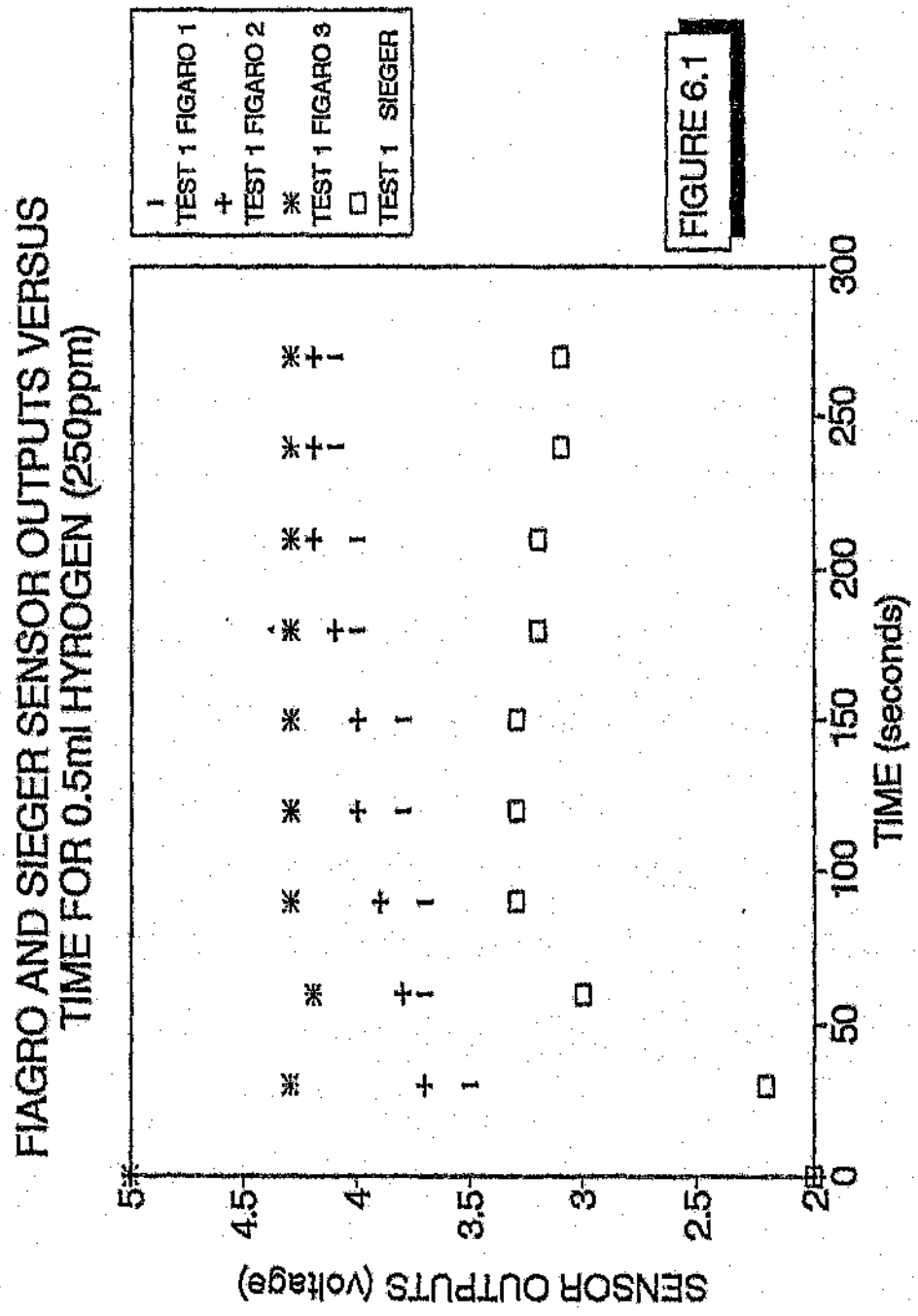


Figure 6.1 Sieger and the 3 Figaro sensor outputs versus time

Figure 6.2 - Sieger and the 3 Figaro sensors outputs versus time for 0.5 ml injected hydrogen. The hydrogen was injected at regular intervals, in 0.5 ml quantities. This figure uses the data from test 2.

Figure 6.3 - The 3 Figaro sensors versus the Sieger sensor for test 2. This graph provides a calibration of the Figaro sensors, assuming the Sieger sensor is accurate.

Figure 6.4 - Maximum Sieger readings versus injected hydrogen concentration. This graph shows the accuracy of the Sieger sensor.

6.6 Conclusions

1. Figure 6.1 and figure 6.2 confirms that the Figaro sensors are not absolutely accurate. Each one will have to be individually calibrated.
2. From figure 6.2 it can be seen that as the Figaro sensor readings increase after reaching a minimum, the Sieger sensors decrease. Both sensors therefore show that the actual hydrogen concentration is decreasing. This confirms the previous results.
3. Figure 6.3 again shows that there is a large spread in the Figaro sensor readings.
4. Figure 6.4 shows that this particular sensor is inaccurate. These results are contrary to the manufacturer's specifications. Presumably this is due to the fact that the sensor unit was replaced locally, and not calibrated accurately.

Note: NUCOR is S. Africa's largest user of the Sieger sensors. They test all their incoming Sieger sensors. Their test results confirm the manufacturer's specifications.

6.7 Recommendations

1. The Figaro sensor is not suitable for an accurate on-line monitor.
2. A few new Sieger sensors should be obtained, the manufacturer's specifications checked. If these are meet, the Sieger sensor can be used in an on-line monitor without calibration. Depending on the design of the on-line monitor, there is the definite possibly of manufacturing the monitors without requiring calibration.

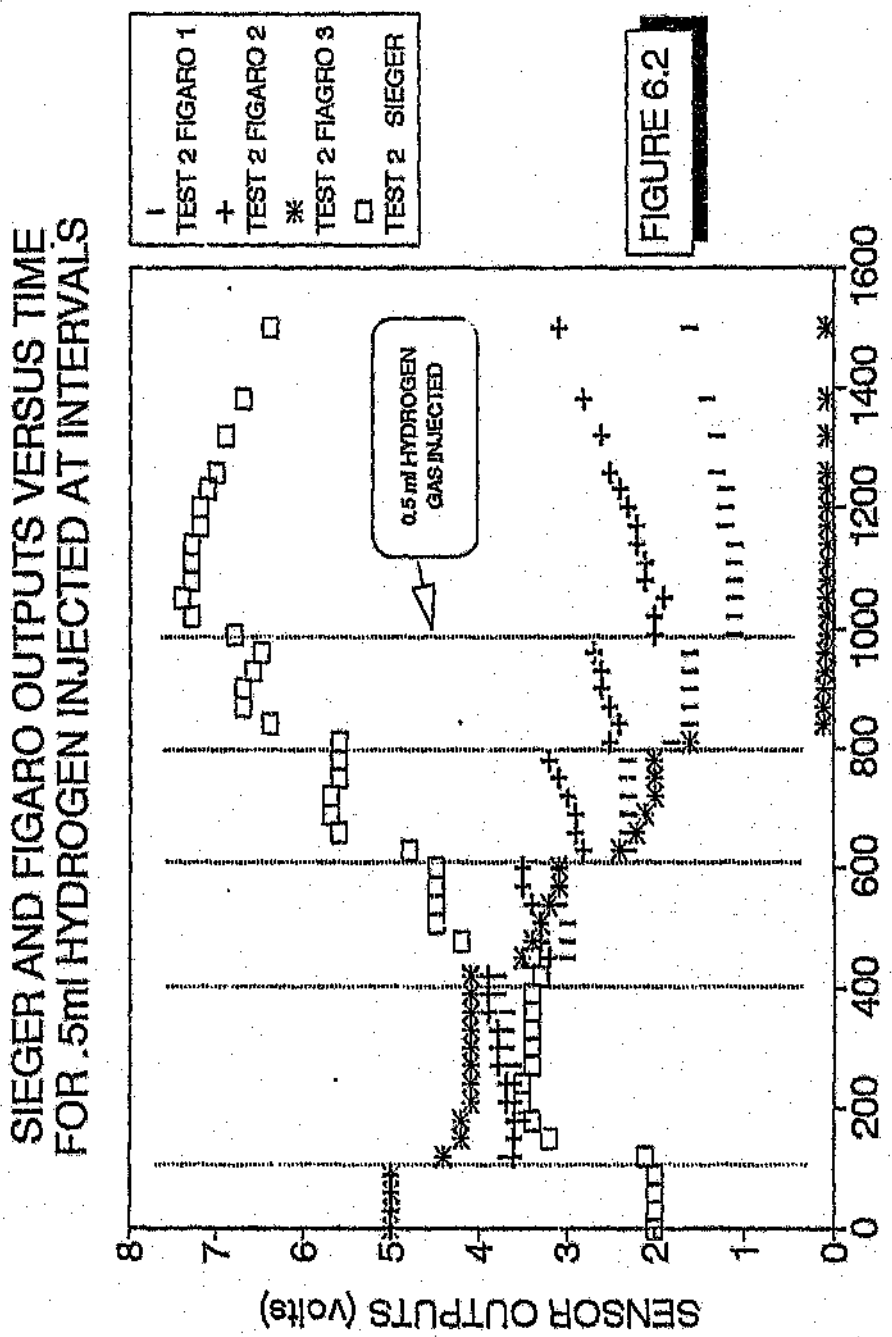


Figure 6.2 Sieger and the 3 Figaro sensor outputs versus time

Figure 6.3 3 Figaro sensor outputs versus the Sieger sensor output

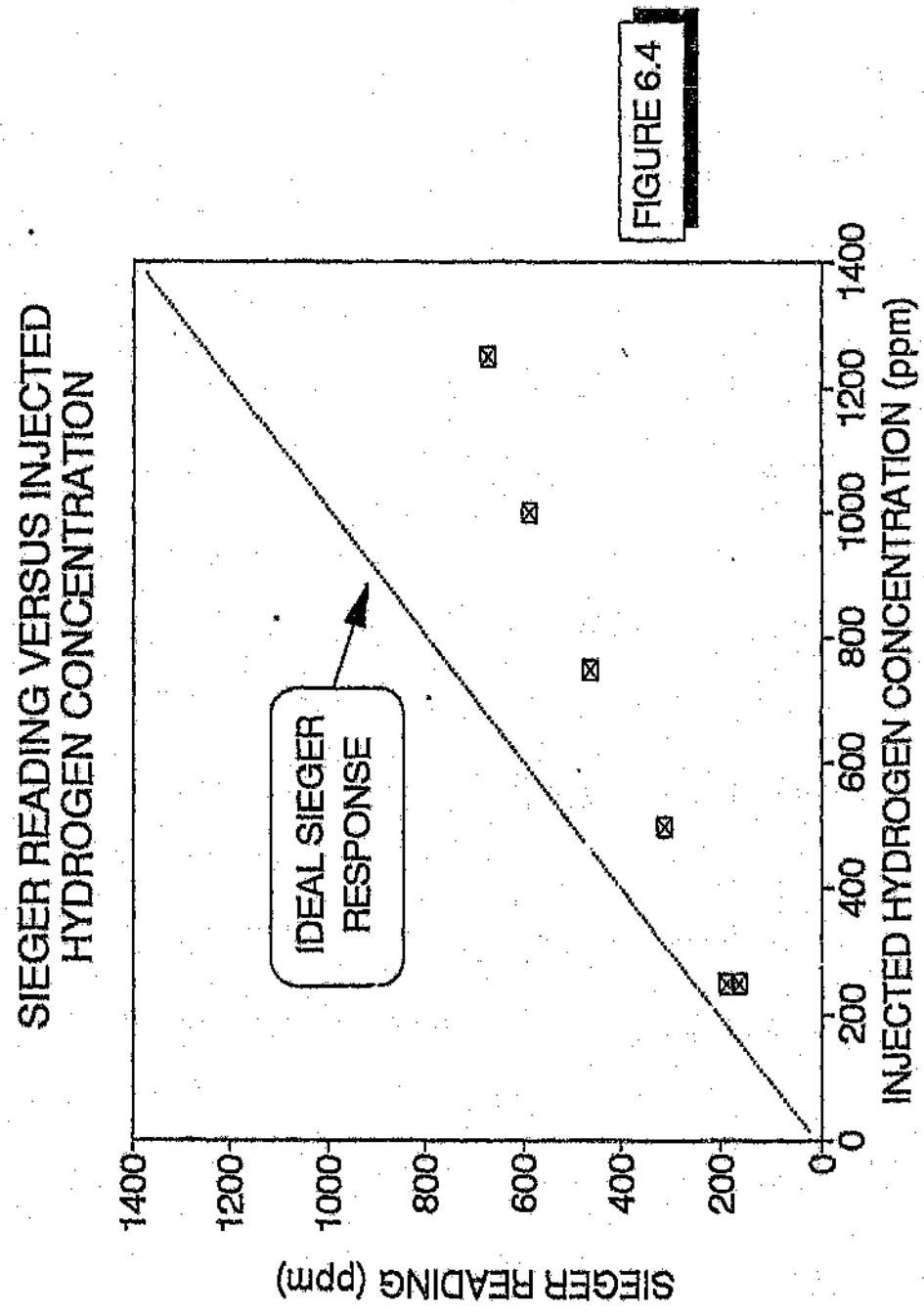


Figure 6.4 Maximum Sieger sensor reading versus injected hydrogen concentration.

7 EXPERIMENT 6

7.1 Title

Comparison between the hydrogen concentration in the oil at different heights.

7.2 Purpose

1. To check whether the position at which the oil is sampled for hydrogen concentration is important.

7.3 Apparatus

1. Experimental CT tank.
2. Sieger sensor. (Has a built in 4-20 mA loop)
3. Fluke datalogger for recording of results from the Sieger sensor onto printed paper.
4. Two 100ml gas-tight syringes for oil sampling.
5. 5ml gas-tight syringe to inject hydrogen gas into the experimental tank.
6. Calibration standard hydrogen gas.
7. Standard 15V power supply to power the sensors.
8. Sample vessels for oil samples.

7.4 Method

All the ports are sealed with special plugs. The top and bottom ports use plugs with septas. The hydrogen gas is injected into the bottom of the tank via the septa. The middle two ports use modified plugs that allow the gas-tight syringes to screw on via a tap. Teflon tape is used on all the screw threads. This allows oil samples to be taken without any air being sucked into the oil sample.

The Sieger sensor is bolted to the underside of the tank's top lid. The CT tank is filled to 3/4 of its height with oil. This allows the top port to be part of the air space above the oil. The CT tank is sealed off to the outside air. The current output of the Sieger sensor is connected across a resistor to convert the output to a voltage that can be read by the datalogger. The Sieger sensor is supplied by a standard 15V power supply.

The datalogger is typically programmed to read the sensors every 30 to 60 seconds for the first hour, and then every hour thereafter. The Sieger output is printed as 2 to 10V output. The Figaro output is printed as 0 to 10V reading inversely proportional to the hydrogen concentration.

Hydrogen concentration gas is injected into the bottom of the tank. The tank is tilted until all the hydrogen gas bubbles through to the top of the tank. The hydrogen gas concentration in the top of the tank is monitored with the Sieger sensor. The experiment is left for the night. The next day two oil samples are taken with the gas-tight syringes. Initially two oil samples were taken from the top middle p[illegible]. The large difference in the readings showed that the dissolved hydrogen gas was not reaching the end of the ports. This was repeated for another two tests. The two middle ports were modified to allow the oil to be sampled from the middle of the tank.

A thin pipe is jammed into the plug. This allows an oil sample to be taken from the middle of the tank at the different heights. The dead oil in the pipe is discarded before the actual oil sample is taken. Two tests were performed.

7.5 Results

For all three tests the acetylene concentration is approximately the same, approximately 50ppm. Incidentally this acetylene is from the previous experiments when arcing was induced in the oil. In the first test, the first oil sample contained 9ppm hydrogen. The second oil sample contained 199ppm hydrogen. In the second experiment both oil samples contained approximately 12ppm hydrogen. In the third test no hydrogen gas was detected.
For the next two tests, the samples were taken at different heights. For the first test, one test contained too little gas from analysis. This was obviously a problem with the degassing apparatus. The second sample contained only 12ppm acetylene, at variance with the above tests. This again indicated a problem with the degassing apparatus.
In the second test, the first sample was contaminated with air from the degassing apparatus. The sample could not be analysed. The second sample contained 44ppm acetylene, which corresponds to the above samples. This indicated that this sample was valid. No hydrogen was detected!

7.6 Conclusions

1. The first three tests show that the dissolved hydrogen gas was not reaching the end of the port.
2. Unfortunately not enough data are available from the second two tests to make any conclusions.

7.7 Recommendations

1. More tests must be done.

8 CONCLUSIONS

8.1 Hydrogen sensors

1. Comparing the Sieger sensor and the Figaro sensor :

The Sieger sensor is expensive at R3000 while the Figaro sensor is cheap at R130. The hydrogen cell used by the Sieger sensor has to be replaced at a cost of R1000.
The Sieger cell has a lifetime of approximately 3 years while the Figaro is supposed to have an unlimited lifetime.
The Sieger cell is supposed to be approximately 5% accurate, while the Figaro cell is totally inaccurate. Each Figaro cell will have to be individually calibrated before use, and probably once year thereafter.
The Sieger cell is stable with temperature and time while the Figaro cell is totally inaccurate if the equilibrium temperature is not reached.
The Sieger sensor has a built in 4 - 20 mA loop, and therefore requires no signal conditioning electronics. The Figaro sensors require signal conditioning electronics for converting the output of the cell to a 4 - 20 mA loop. The electronics will cost approximately R200.

2. Both sensors are therefore not suitable for a low cost hydrogen on-line monitor (<R5000). The initial price of the Sieger sensor is high, and requires expensive hydrogen cell replacements every 3 years. The Figaro sensor requires laboratory calibration approximately every year. This cost, in man-hours, could be prohibitive if the monitor is far in the field. Assuming that the monitor requires 2 hours for removing from the tran former, 2 hours for laboratory calibration, and 2 hours for installing, the cost would be approximately 6 x R50 = R300 + Courier service from the local region to E.I and back. Note that this cost could easily exceed the cost of replacing the Sieger sensor cell, if the Sieger sensor is used.

3. If the cost of the on-line monitor is less of a consideration, the Sieger sensor is the best choice. The Figaro sensor is not suitable for accurate measurements, and will only be suitable for a go / no-go type of monitor. Unfortunately this type of monitor is not suitable for reliable on-line monitoring. A monitor must rather give an alarm for an user selectable increase in the hydrogen concentration over a certain time.
Depending on the design of the monitor, using the Sieger sensor has the potential of requiring no calibration prior and during use on the transformer. This implies that local manufacture of the instrument is feasible.

8.2 Monitoring the hydrogen concentration in the air space of a transformer

1. This would be the ideal way of on-line monitoring of current transformers. All the experiments performed showed fast and consistent increases in the hydrogen concentration in the air space of the experimental tank. This method would be also cheap, because no apparatus is required for removing the dissolved hydrogen gas from the oil. Unfortunately this method cannot be implemented due to safety considerations. No modifications can be made to the high voltage side of the current transformers. Also no leads can be taken from the high voltage side to ground level. The only way that this method can be implemented, is if the hydrogen monitor is designed into the current transformers at manufacture.
2. This method could be implemented on high voltage transformers. While not possessing the problems associated with current transformers, more research will have be conducted. If this does work, this would be a very cheap method, relative to the price of large high voltage transformers, of monitoring high voltage transformers.

8.3 Membrane separation of the dissolved hydrogen gas from the oil

1. Using a membrane to separate the dissolved hydrogen gas from the oil has a number of disadvantages. There are two methods of using the membrane. The one method is to allow the hydrogen gas dissolved in the oil to reach equilibrium with the hydrogen gas in the gas chamber on the other side of the membrane. This was the method used in the hydrogen on-line monitor designed by Hitachi. The problem with this method is that the time taken to reach equilibrium is inordinately long - 72 hours in the case of the Hitachi on-line monitor. Also the temperature effect on the rate of diffusion has to be taken in account.
The other method is use the membrane in such a way that the hydrogen gas that diffuses through the membrane is less than the hydrogen gas used up by the sensor. This is the method used by the Hydran. This method is very temperature sensitive because the rate of diffusion has an exponential rise for a temperature rise.
2. It is very difficult to obtain suitable membranes in S.A. Eventually the membrane used in the designed on-line monitor was specially manufactured by Engineering Investigations Applied Chemistry department. Unfortunately the consistency between the different membranes made cannot be guaranteed. The final on-line monitor will still require a standard commercial membrane for easy manufacture of the on-line monitor.
3. The membrane has to be in contact with moving oil. The experimental results clearly show that no reliable results can be obtained from the on-line monitor if the monitor is bolted to a port a small distance from the oil body.

8.4 Oil sampling techniques

1. Large problems were encountered in taking reliable oil samples for hydrogen gas concentration. Acetylene, and to a lesser degree the other hydrocarbon gases, are not very sensitive to the sampling method.

2. The gas-tight syringes proved reliable for oil sampling. Unfortunately their cost , approximately R550, rules out the possibility of using the syringes for general oil sampling. The tin sample vessels used, are probably still the most cost effective method for general sampling. But the hydrogen gas level should not be used to assess the condition of the transformer. Acetylene is the best gas to check for, but will not indicate increases in partial discharge and other low level faults.
3. If any oil samples are taken, it is most important that there are no air bubbles in the oil. This applies equally to using the gas-tight syringes as to using the standard sample tins. The hydrocarbon gases dissolved in the oil to varying degrees diffuses into any air bubbles in the oil. Most of the acetylene will stay in the oil, while most of the hydrogen gas will diffuse into the air bubbles.

8.5 Hydran on-line monitor

1. The particular Hydran monitor that was tested was inaccurate, despite electronic calibration prior to the experiments.
2. The Hydran is very temperature sensitive. This was confirmed by the Hydran reading on an actual transformer in the field.
3. The Hydran is sensitive to any air bubbles in the oil in contact with the membrane.
4. The Hydran must be in contact with the main oil body or in the stream of the oil flow for reliable measurements. The manufacturers recommendations on this must be followed.
5. The cost of the Hydran precludes wide usage on current transformers.

8.6 Effect of the height at which the monitor is bolted on the transformer

1. The results indicate that no dissolved hydrogen gas reaches the ends of the ports.
2. No conclusions can be made about the height at which the sampling is done due to the lack of data.

9 RECOMMENDATIONS

9.1 Hydrogen sensors

1. A number of Sieger sensors should be obtained, and evaluated for accuracy and repeatability
2. If the Sieger sensor conforms to the manufacturer's specifications, it should be used for future designs rather than the Figaro sensor.

9.2 Monitoring the hydrogen concentration in the air space of a transformer

1. Tests should be conducted on the high voltage transformers to ascertain whether this method is suitable for on-line monitoring. This will require an accurate on-line monitor to compare the hydrogen concentration in the air space to the hydrogen concentration in the oil.

9.3 Membrane separation of the dissolved hydrogen gas from the oil

1. Alternative methods for separating the dissolved hydrogen gas from the oil should be used for future on-line monitor designs.
2. This method must also be able to sample the oil deep in the transformer for accurate on-line monitoring.

9.4 Oil sampling techniques

1. An experiment should be setup to try quantify the errors due using the standard sample vessels for the various gases.

2. This must be repeated using the gas-tight syringes to confirm whether the syringes are suitable for accurate measurements. If the results are positive, the syringes could be possibly used for strategic transformers suspected of partial discharge activity.
3. No air bubbles must be present in the sample vessels.

9.5 Hydran on-line monitor

1. A number of Hydran monitors should be tested for accuracy using an known mixture of hydrogen gas and oil.
2. Any results taken must take into account temperature variations to prevent false alarms.

9.6 Effect of the height at which the monitor is bolted on the transformer

1. The on-line monitor must not be bolted on to a transformer via a port. It should be in direct contact with the main body of the oil.

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