Transformer Oil DGA Monitoring Technology Study 2015

Jason C. Dennison – SD Myers Inc.
Jon M. Trout, PE – SD Myers Inc.

Abstract – As use of dissolved gas analysis (DGA) monitors increases as a growing component of transformer maintenance and reliability, it is imperative to understand the capabilities of monitors in their ability to align with conventional laboratory results and detect gas-related changes from a baseline. SDMyers studied DGA monitors from several manufacturers through experiments over 18 months. Technologies included in the study were gas chromatography, photo-acoustic spectroscopy, solid-state palladium, thermal conductivity detection, and selective membrane methods. This paper summarizes conclusions from that study based on technology employed.

Index Terms – DGA, dissolved gas analysis, monitoring, monitor technology, transformer monitoring, DGA monitor, detection, maintenance, reliability

Introduction

Transformer monitoring is a rapidly growing field. It is estimated that the market for DGA monitors will increase from $113 million in 2012 to more than $755 million in 2020 [1]. This includes expansion from predominantly utility and generation monitoring into wider and broader application throughout the power grid and into industrial application as well. It is increasingly common to purchase DGA monitors at time of purchase of new transformers, and adding monitors to critical in-service transformers is becoming a significant component of transformer maintenance and reliability programs.

DGA monitor manufacturers use many different technologies for the purpose of dissolved gas detection in active monitoring. The major manufacturers predominantly use gas chromatography (GC), photo-acoustic spectroscopy (PAS), solid state (SS), thermal conductivity detector (TCD), or selective membrane (SM) based sensors. These technologies have been in active use for several years, though GC is currently the only gas detection method referenced in IEEE standards for gases generated in oil-immersed transformers [2]. Other emerging DGA monitoring technologies not included in this study include non-dispersive infrared (NDIR) and carbon nanotube (CNT).

Experiment Setup

The primary purpose of the study was to understand the detection capabilities of DGA monitors; accordingly, the experiment design mimicked typical oil conditions with respect to heat and mixing, while not attempting to directly replicate a transformer.

The test setup was located indoors. Monitors featured enclosures similarly protected against ingress of dust and water (IP55 to IP66) for operation from –50°C/–40°C to +55°C.

The test setup for the experiments involved an 80-gallon steel test tank filled with 60 gallons of oil. The test setup used a vented tank with a nitrogen blanket applied during the test runs.

The oil circulated through a series of heaters to maintain the oil at 60°C (140°F), using multiple thermocouples to ensure consistent heating and avoid overheating the oil. The oil in the test tank was also continuously mixed, ensuring that the oil was well mixed and not stagnant.

Multiple DGA Monitors were connected in a heated monitoring loop with continuous oil flow. The monitoring loop also included a sample port for drawing oil samples for conventional lab DGA performed by SDMyers' Diagnostic and Analytical Services.

For test runs, a target gas or gases were injected into the heated loop through a regulator attached to gas cylinders containing DGA gases. At the completion of each experiment, the oil was passed multiple times through a vacuum degasser to return the oil to a like-new condition.

Monitors in this study were utilized as installed and configured by the monitor manufacturers. No additional adjustments to parts-per-million (PPM) readings output were made during installation and setup, though most monitors in this study feature the ability to adjust PPM output for the purpose of aligning monitor calibration with a specific conventional lab.

Table 1 below summarizes the monitors included in this study by study label, monitor technology, and gases detected for each monitor. Monitors with gases detected accompanied by a percentage character (%) indicate the monitor is sensitive to certain gases while not directly reporting 100% of the gas in the system (i.e. the displayed PPM is a composite of more than just the main gas).

Label	Technology	Gases Detected
PAS-1	Photo-acoustic spectroscopy	H2, C2H2, CO
PAS-2	Photo-acoustic spectroscopy	H2, C2H2, C2H4, C2H6, CH4, CO, CO2, O2
GC	Gas chromatography	H2, C2H2, C2H4, C2H6, CH4, CO, CO2, O2
SS-Pd	Solid state Palladium	H2
SM	Selective Membrane	H2, CO(%), C2H2(%), C2H4(%)
TCD	Thermal Conductivity Detector	H2, CO
Lab (GC)	Gas chromatography	H2, C2H2, C2H4, C2H6, CH4, CO, CO2, O2, N2

Table 1 – Monitor technologies included in this study.

The results summarized in this paper are the culmination of more than 30 experiments spanning 18 months designed to understand immediate and long term DGA monitoring consistency and behavior.

General Findings

In general, this study showed that all monitor technologies are proficient at detecting fault gases. This is particularly true with respect to detecting gas value changes from a baseline, which is arguably the most critical capability of online DGA monitoring.

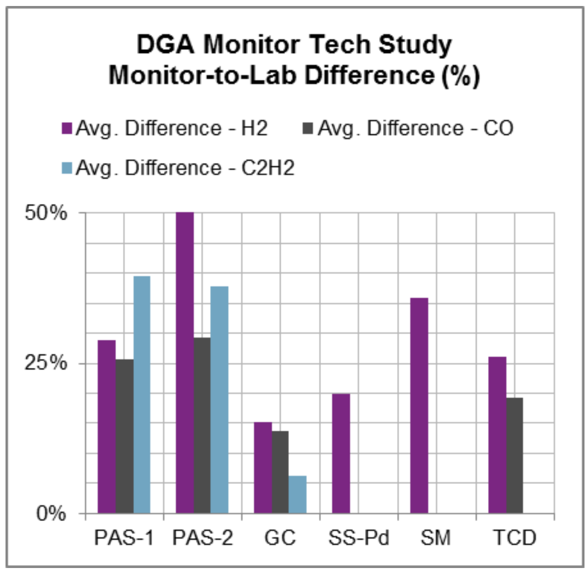
Monitor-to-Lab Difference

During testing, it was common for monitor PPM values to differ from conventional laboratory PPM values. Graph 1 below shows the average absolute difference in measurement between the various monitor technologies and conventional laboratory GC results for Hydrogen, Carbon Monoxide, and Acetylene; a lower percentage indicates closer match to the conventional laboratory GC results. This graph shows how the monitors differ from the lab results across several experiments. Difference displayed in Graph 1 below is:

$$\% \, Difference = \left| \frac{(Monitor\ Result - Lab\ Result)}{Lab\ Result} \right|$$

Refer to Table 1 as to the gases reported by each monitor.

These results show the technologies exhibit variability compared to each other and conventional laboratory GC results. The variability does not appear to be extreme in context of other studies, such as inter-laboratory testing showing variability between conventional laboratories [3]. While this variability is not a cause for significant concern, it does reinforce that monitoring is well suited as supplemental to routine testing and inspection, rather than as a replacement of elements of routine maintenance. The interpretation and diagnosis of DGA data is critical as an element of monitoring. Expert analysis should incorporate monitor data, routine interval testing results, inspection data, and any other available information that may provide insight into the condition of a transformer in order to develop the most effective response to potential incipient conditions.



Graph 1 – Monitor result difference (absolute value %) from conventional laboratory result.

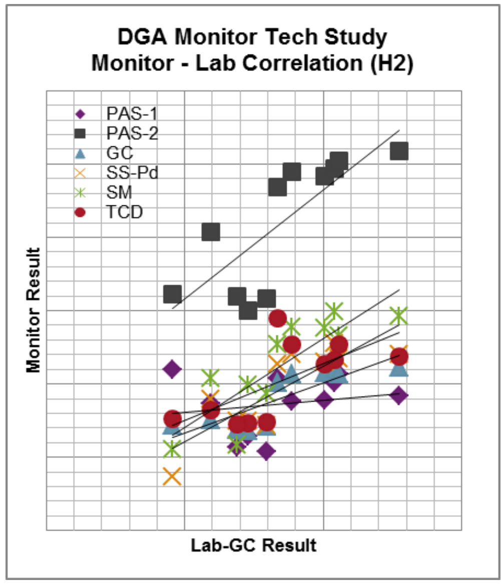
In Graph 1 above, monitor PAS-2 exhibits a significant departure in Hydrogen measurement. For some experiments, this monitor reported Hydrogen PPM much higher than other monitors and conventional laboratory PPM. The monitor was serviced and after service, the Hydrogen PPM results shifted to align more closely with other monitors and conventional laboratory GC results. The data is not excluded from graphs included in this report, as it shows further evidence that the reporting of changes in gas values from a baseline was repeatable. Recall that monitor SM reports a composite PPM result including percentages of other gases in addition to Hydrogen. As the raw value from that monitor was used, a direct comparison of Hydrogen PPM values against this monitor is imperfect but still shows general alignment with other technologies.

Monitor Detection – Group Behavior

The most important role for a DGA monitor is the repeatable reporting of DGA values in order to provide advance warning of incipient issues as gas values change from steady-state readings. Graphs in this section depict monitor results versus conventional laboratory GC results in order to show monitor behavior as a group. Complete match with conventional lab GC would result in a 45° trend line passing through the origin and sloping upwards from left to right; this would indicate all methods and technologies showing the same results. A line with a shallow slope indicates a monitor reporting lower values compared to conventional lab; a steeply sloped line indicates a monitor reporting higher values.

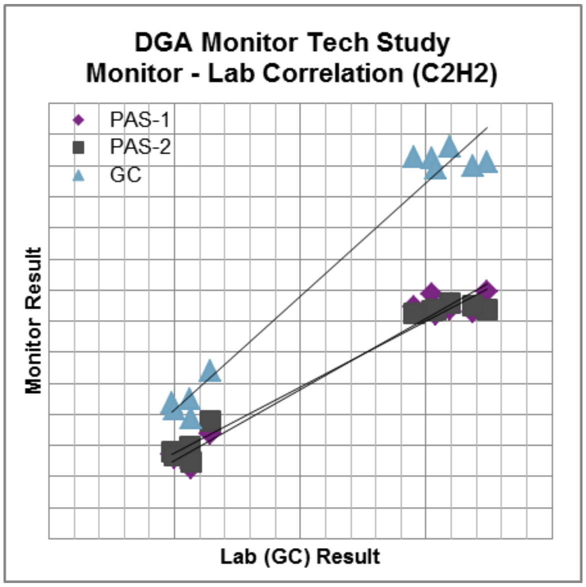
Summarily, these graphs show that all monitors exhibit similar positive trend lines, suggesting that all methods and technologies are capable of detecting changes in DGA gas values in a system across multiple experiments.

Graph 2 below shows the widest array of technologies, as all monitors in this study are able to detect Hydrogen. All trend lines indicate a positive slope that reinforces monitor capability to detect changes. The graphs that follow support the finding that all technologies represented are proficient at detecting changes to gas values in the system when compared to each other.

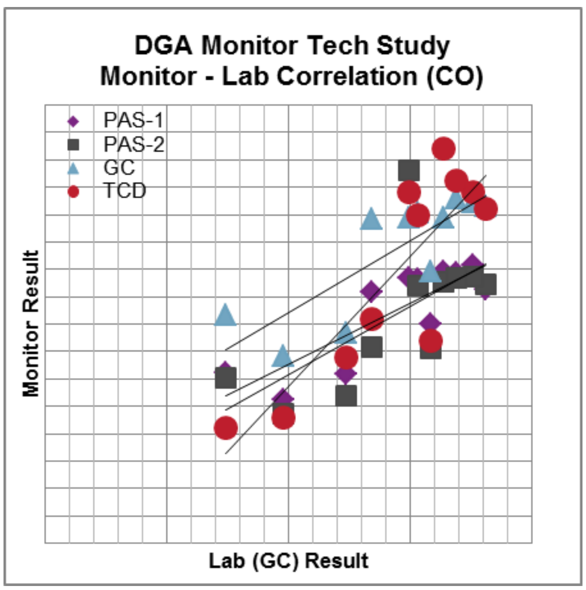


Graph 2 – Graph depicts monitor PPM compared to conventional laboratory GC PPM results for Hydrogen. SM reports a composite value, not a direct Hydrogen PPM value.

Graph 3 below shows alignment of Acetylene results between reporting monitors and conventional laboratory GC. Graph 4 that follows shows similar acceptable general alignment of CO results between monitor and conventional laboratory GC. These charts are representative of the general alignment between monitors in this study as compared to conventional laboratory GC.



Graph 3 – Graph depicts monitor PPM compared to conventional laboratory GC PPM results for Acetylene.



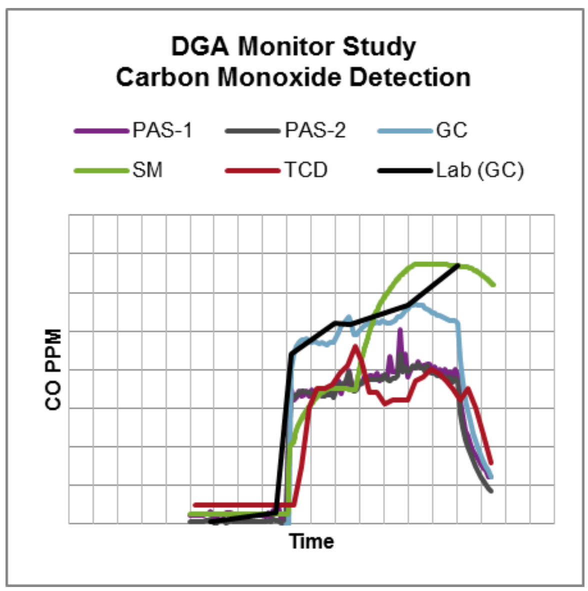
Graph 4 – Graph depicts monitor PPM compared to conventional laboratory GC PPM results for Carbon Monoxide, showing good general repeatability across all reporting technologies.

Monitor Detection – Gas Value Changes

Monitor capability to detect changes in gas values in a system is critical to a monitor's use as a component of a preventative and predictive maintenance tool.

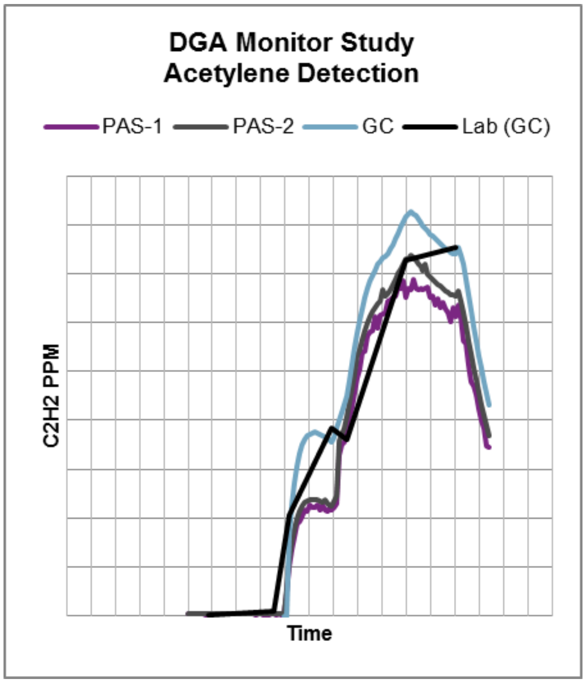
A sample of DGA gas values reported over time is included in the graphs below. In general, these graphs show that all monitors are proficient at detecting changes in gas values in a system.

The following graphs depict examples of DGA gas values as reported over time during several experiments. Graph 5 shows Carbon Monoxide over time as the gas was introduced to the system. Recall that SM reports a composite value that includes a percentage of other gas values in addition to Carbon Monoxide.



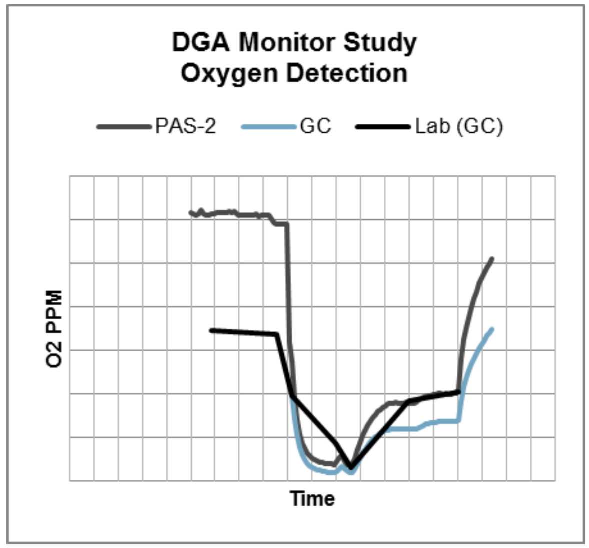
Graph 5 – Graph depicts monitor and conventional laboratory GC PPM results over time for Carbon Monoxide.

Technologies reporting Acetylene showed good alignment both between monitors and in alignment with conventional laboratory GC results. An example of monitor behavior is shown in Graph 6 below.



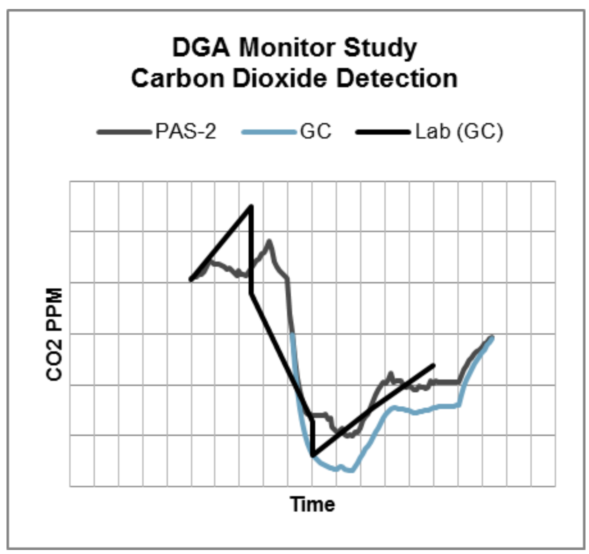
Graph 6 – Graph depicts monitor and conventional laboratory GC PPM results over time for Acetylene.

Graph 7 below shows Oxygen values over time from an experiment where Acetylene was added to the system. The significant drop in Oxygen values as the experiment began and the return to prior levels at the end of the experiment shows the capability of the reporting technologies in detecting system changes involving Oxygen.



Graph 7 – Graph depicts monitor and conventional laboratory GC PPM results over time for Oxygen.

Similarly, Graph 8 below depicts Carbon Dioxide results over the same experiment showing that each technology detected the system change adequately.



Graph 8 – Graph depicts monitor and conventional laboratory GC PPM results over time for Carbon Dioxide.

Hydrogen

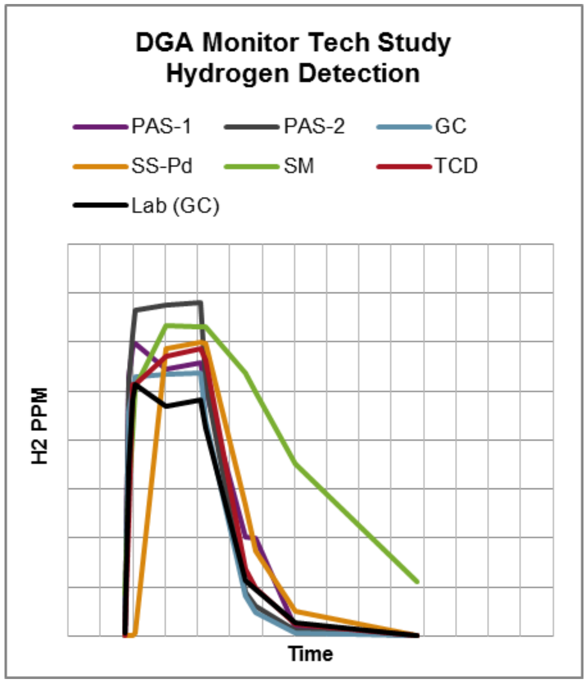
Hydrogen is of particular interest in the study, as it is an indicator gas generated in the majority of active fault conditions. Additionally, several manufacturers offer Hydrogen monitors as a lower cost DGA monitoring solution compared to multi-gas monitors.

A review of Hydrogen data provides further evidence that the DGA monitor technologies in this study are proficient at detecting changes in Hydrogen values in a system.

Hydrogen presents a practical challenge in setting alert or alarm limits in transformer monitoring, as Hydrogen is generated in most fault conditions detected by DGA. Setting the sensitivity of alerts and alarms to provide early detection of low temperature faults may result in additional "false alarms", where natural variation in gas concentration or stray gassing may trigger an alert or alarm when no fault condition exists. Alternatively, setting Hydrogen alert and alarm limits higher may avoid these false alarms at the heightened risk of missing an alert for a low temperature fault or for arcing, in which a relatively small amount of Hydrogen is generated for a serious fault condition.

For any gas, it is imperative that monitor owners employ DGA expertise in reviewing available data when alert or alarm conditions are triggered to ensure appropriate response. This is particularly true for Hydrogen monitors, which act as a "check engine light" indicator for potential incipient fault conditions. These monitors have an elevated risk of being regarded as a nuisance if alarm set points are not intelligently set and monitored by personnel with DGA and transformer expertise.

Graph 9 below shows the detection of Hydrogen over time. Hydrogen gas was introduced in the system to observe monitor detection over time, as Hydrogen has low solubility in oil and will quickly leave the oil. Each monitor displayed good ability to report the change in Hydrogen as well as the drop-off of Hydrogen values after introduction.

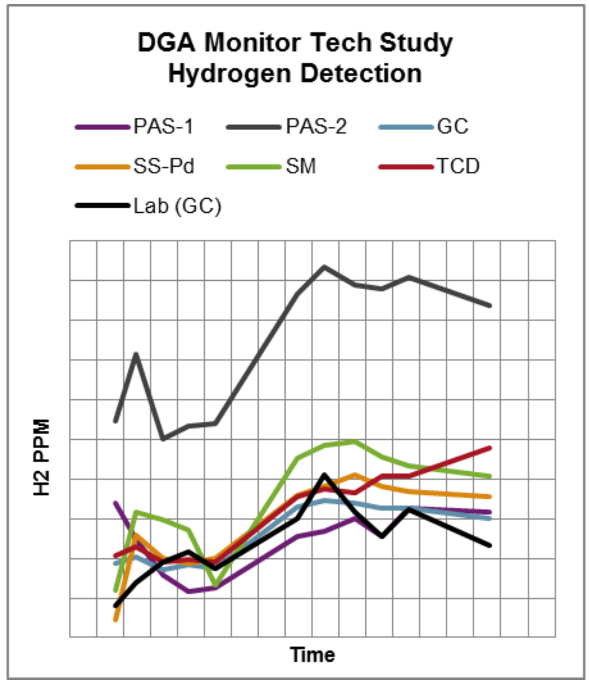


Graph 9 – Graph depicts monitors and conventional laboratory indicating very similar PPM and rate of change for Hydrogen detection during a short-term experiment. Also shown is a "tailing lag" of reported values from SM.

Graph 9 above displays a common characteristic of monitor SM, where a return to steady-state values for DGA gases displays much more quickly by the other technologies. This “tailing lag” of readings may be a general behavior of the selective membrane and fuel cell technology, and/or may be an artifact of the monitor technology that reports a composite PPM reading including Hydrogen, Carbon Monoxide, Ethylene, and Acetylene, rather than an explicit Hydrogen PPM reading. In these experiments, a mixture of gases that included Hydrogen, Acetylene, and Carbon Monoxide was introduced in the system in elevated amounts. As these gases have differing solubility in oil, the tailing lag is due to higher solubility in oil of Carbon Monoxide and Acetylene, at 9% and 400% by volume respectively, compared to Hydrogen at 7% by volume [4]. This behavior did not appear to affect the ability of the monitor to detect changes in the system.

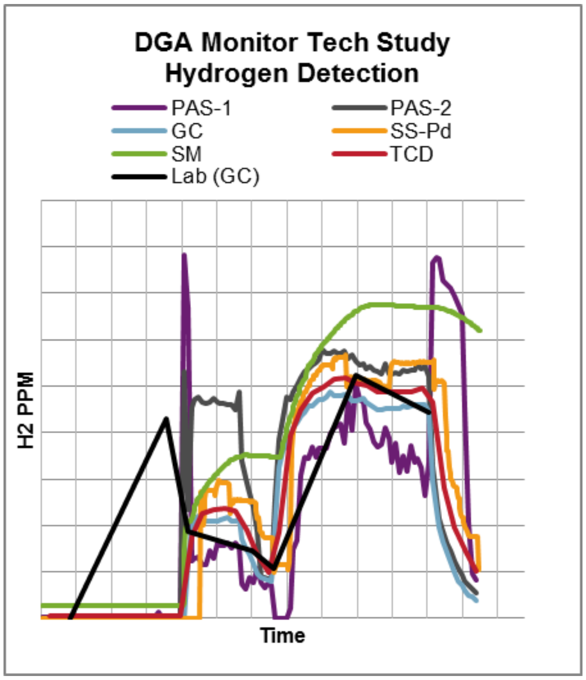
It is worth noting that any monitor that reports a composite PPM value may exhibit similar behavior compared to explicit measurement. The ability to detect incipient issues may be similar to other monitor technologies and a return to lower values may appear different due to the composite value including readings for gases that have differing solubility in oil.

Graph 10 below shows general monitor behavior for Hydrogen detection wherein one monitor yielded higher Hydrogen PPM values, yet still reported very similar results with respect to magnitude of change in the system. In practical application, the monitor technology would still produce rate of change or PPM alarms, provided the initial set points for alarm limits were set from a baseline from that monitor. Despite reporting exaggerated PPM results compared to other monitors and conventional laboratory GC, the change in the system was still detected by the monitor.



Graph 10 – Even with differing magnitude of results, all monitors display very similar magnitudes of change from baseline for Hydrogen detection during a short-term experiment.

Graph 11 below shows results from a weeklong experiment in which a mixture of gases was introduced throughout the duration of the experiment. The similar behavior among monitors is noted with respect to reporting a change of gas values in the system.

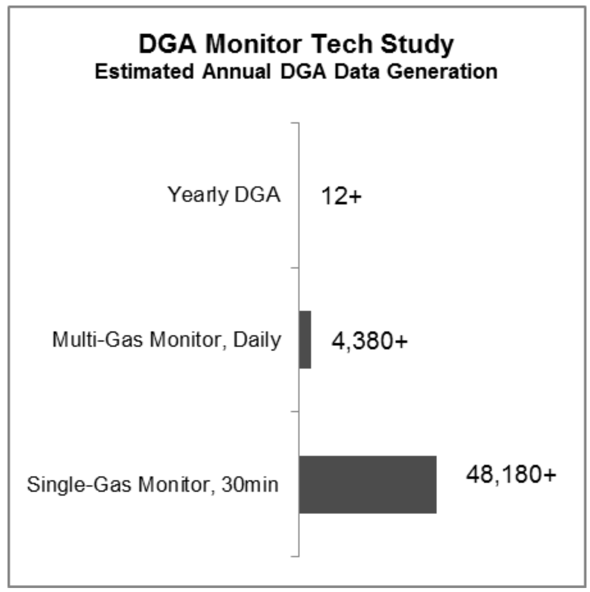


Graph 11 – Data from long-term spike-and-sample experiment over several days – all monitors detected system changes.

Data Generation

Over the course of this study, it became apparent that the amount of data being generated by DGA monitors is significantly greater than what is generated by routine interval testing. Typical annual routine DGA testing generates 12 pieces of information – sample date, nine gas values, total combustible gases value, and total gas value. Typical 8 or 9 gas DGA monitoring generates the same data much more frequently – and most multi-gas monitors also have the ability to record additional information such as oil temperature, pressure, load, and moisture. If a multi-gas monitor is configured to measure daily, the available DGA data compared to routine interval testing increases by orders of magnitude.

Single gas monitors often take samples more frequently, on the order of every 20 – 30 minutes. These monitors typically report far fewer data (date, PPM, and rate of change values) yet the frequency of measurement generates an impressive amount of data – greater than 52,000 data points over the course of a year. Actual amounts of data will vary slightly based on monitor setup and routine calibration frequency.



Graph 12 – Data generation comparison between routine interval testing and different monitoring technologies.

Monitor manufacturers typically offer software for data management that may include diagnostic tools. Data retrieval can be a challenge if monitors are not connected to a network, and interpretation of the data can be challenging without DGA and transformer expertise. Monitor owners need to plan how to include monitor data as an element of their transformer reliability approach. The increase in data is significant and can rapidly become chaotic in the absence of DGA and transformer expertise.

Summary

Overall, the technologies represented are clearly capable of detecting changes in gas values from a baseline. In all tests, monitors proved capable of detecting changes in gas levels appropriate to each monitor's capability and sensitivity. The ability to detect changes in steady state systems is arguably the most important aspect of continuous DGA monitoring and in this respect, all monitors performed very well.

The consistency of PPM value reporting as compared to conventional laboratory GC results showed variability from all monitors. Across all experiments, no technology emerged as matching conventional lab results more closely or consistently than others.

Employing DGA diagnostic expertise to the considerable amount of data generated in monitoring is a critical element of a monitoring strategy. Whether using a single- or multi-gas monitor, DGA and transformer expertise is paramount in understanding what the data indicates and formulating the correct response to improve the reliability of transformers. Responding to potential incipient issues based on expert judgment of DGA and all available information is the foundation for a cost-effective, intelligent reliability approach to transformer maintenance.

The monitor technologies studied employ continuous monitoring capability, and can dramatically increase the amount of data available to assist in making intelligent decisions in transformer management. Conventional laboratory GC continues to be the standard for detection of dissolved gases, and continuous monitoring via the technologies represented in this study paired with DGA and transformer expertise can be a value-added supplement to routine testing and inspection as a component of preventative maintenance and reliability.

Acknowledgements

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