

# A Comparison of Amperometric and Optical Dissolved Oxygen Sensors in Power and Industrial Water Applications at Low Oxygen Levels ( $< 5 \mu\text{g} \cdot \text{kg}^{-1}$ )

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## ABSTRACT

In this paper, the performance of both optical and amperometric oxygen sensors in both fossil and nuclear power plant applications is compared and discussed. The results of independent tests conducted to evaluate the suitability of a new sub- $\mu\text{g} \cdot \text{kg}^{-1}$  optical sensor for use in power plants and industrial applications of different types are presented. The issues of stability and repeatability, the influence of dissolved hydrogen and performance under flow variation are addressed. In terms of repeatability, accuracy, response time and maintenance efforts the optical sensor is shown to be comparable or superior to amperometric sensors.

## INTRODUCTION

The majority of existing dissolved oxygen analyzers use amperometric sensors. Whilst these are renowned for their accuracy and reliability, issues encountered by users include maintenance complexity and frequency in addition to flow dependence and calibration needs. In more complex applications, amperometric sensors suffer from interference when measuring in the presence of high levels of hydrogen – this often results in negative readings and an unreliable measurement method.

Luminescence technology has been used in power plants since 2006. This type of sensor has shown significant reductions in maintenance complexity and frequency but has been limited by its accuracy, with use generally confined to oxygenated treatment environments. In 2009, the first luminescent oxygen sensor with a sub- $\mu\text{g} \cdot \text{kg}^{-1}$  accuracy for use in power plants was launched.

In this paper, we compare and discuss the performance of both optical and amperometric oxygen sensors in both fossil and nuclear power plant applications. This information is supported with the results of independent tests conducted to evaluate the suitability of the new sub- $\mu\text{g} \cdot \text{kg}^{-1}$  optical sensor for use in power plants and industrial applications of different types.

## OXYGEN MEASUREMENT

Dissolved oxygen is one of the key parameters that must be monitored and controlled in the power industry to effectively minimize corrosion due to oxidation. Numerous guidelines exist from standards bodies on different chemistry methods that can be applied to effectively manage oxygen levels. Fossil power plant chemistries, including all-volatile treatments (AVT) for both reducing (AVT(R)) and oxidizing (AVT(O)) chemistries, along with oxygenated treatment (OT), allow strict control of oxygen levels to minimize corrosion [1].

Within nuclear power plants (NPPs), oxygen measurement is complicated somewhat both by the radioactive material in the sample and the high levels of hydrogen often found in primary cycle chemistries on pressurized water reactors (PWRs, or VVERs) and in the balance of boiling water reactors (BWRs).

Hydrogen injection in NPPs using hydrogen water chemistry (HWC) eliminates oxygen traces through the recombination of oxygen and hydrogen to create water, but most oxygen sensors suffer from interference from elevated hydrogen levels. The critical nature of the hydrogen/oxygen mixture means accurate measurement accounting for any hydrogen interference is essential.

The effects of hydrogen present in water can also be seen in stator water cooling applications. The most commonly used chemistry is a low oxygen approach, with a typical range of 1–10  $\mu\text{g} \cdot \text{kg}^{-1}$  oxygen, but this cooling water is generally saturated with hydrogen [2]. Again, for safety in addition to corrosion control reasons, the oxygen level must be accurately measured.

## POWER INDUSTRY TRENDS

Over the past decade a number of trends have started to gain pace within the power sector, driving a change in instrumentation requirements for operations managers and plant chemists.

Firstly, maintenance and operations budget cuts have resulted in fewer plant personnel. This in turn has forced plant personnel to optimize their daily work even further and reduce their maintenance and calibration workload. Accompanied by the switch to inline/in-process rather than lab measurements, this puts additional time pressure on maintenance personnel.

Secondly, as the cost of building new power plants spirals upwards, many operators now look to plant life-extensions as a solution to bridge gaps in production capacity at a lower investment premium. Construction cost increases are compounded by fears over the cost of new carbon capture systems often demanded on new plants.

Clearly, plant extensions are only possible if the heart of any power plant, the water-steam circuit, can be well managed and maintained – this augments the importance of chemistry managers and the role of reliable instrumentation in plant operations.

Thirdly, there are a growing number of peaking plants in the power sector, especially with the advances in and environmental benefits of combined cycle gas turbine peaking plants [3]. Peaking plants experience more power-up/-down cycles than base-load plants and each of these results in high oxygen concentrations during the start-up. This in turn leads to higher instrument maintenance of amperometric sensors for oxygen measurement, a real problem for operations managers looking for low maintenance systems.

These major trends have altered power plant operational needs. This paper will build on these trends by looking for oxygen measurements that are accurate, reliable, stable, and above all, that require low or zero maintenance.

Given these industry trends, different chemistry guidelines, and the multitude of measurement options and vendors available today, we will candidly discuss two popular technologies, amperometric and optical measurement systems, along with the benefits and limitations of each.

## BACKGROUND AND HISTORY OF OPTICAL OXYGEN MEASUREMENT

Optical measurement of oxygen has been discussed in a number of different papers and is now widely accepted in several industries including for monitoring aquatic biology in wastewater [4], blood gas analysis [5], fermentation control in biotechnology processes [6], wine micro-oxygenation [7], and wastewater oxygen analysis [8].

The use of Luminescent Dissolved Oxygen (LDO®) sensors for the measurement of oxygen is now accepted by ASTM [9] – with tens of thousands of units in use globally, LDO® measurement has been rapidly adopted by users in many industries.

Optical measurement started with the measurement of relatively high oxygen levels, with measurements at  $\text{mg} \cdot \text{kg}^{-1}$  levels now widely accepted and used in process.

Technology advances over the past three years have resulted in  $\mu\text{g} \cdot \text{kg}^{-1}$  measurement systems in the power industry [10]. Accurate and consistent measurement at levels below  $10 \mu\text{g} \cdot \text{kg}^{-1}$  was initially limited due to the accuracy and detection limits available at the time; however since 2009, accurate measurement at levels below  $1 \mu\text{g} \cdot \text{kg}^{-1}$  has been possible.

## PRINCIPLE OF MEASUREMENT

Optical sensing of oxygen is based on the measurement of the red fluorescence of a dye/indicator illuminated with a modulated blue light as shown in Figure 1.

The presence of oxygen results in a phase shift of the red fluorescence light when compared to the modulated blue light source. By measuring this phase shift, it is possible to make a direct measurement of the oxygen concentration in the sample. This technique has been discussed in much greater detail in a paper by Dunand et al. [11].

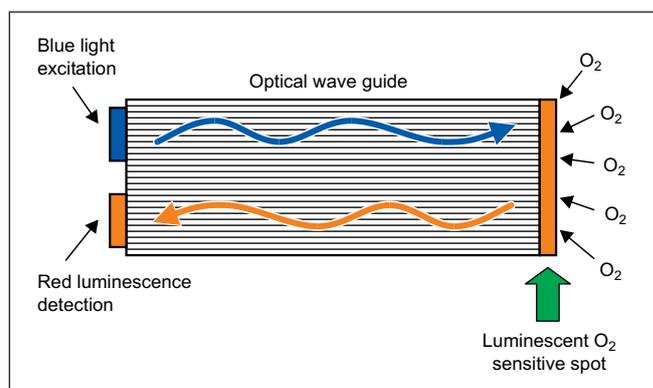


Figure 1:  
Principle of optical oxygen detection using fluorescent dye.

## SYSTEM CALIBRATION

Calibration is the bane of most chemistry engineers – when accurate measurement is important, more frequent calibration is often applied to reduce the risk of measurement drift. Often time consuming, awkward and cumbersome, chemicals and standards are needed for the intricate calibration and verification of oxygen sensors.

Many amperometric oxygen sensors require a two-point calibration – the zero-point and the slope (via a standard calibration sample). In contrast, the Orbisphere amperometric sensor only requires a single-point calibration in air to determine the slope due to its "true zero" – to this day, this sensor is still seen as the industry reference in oxygen measurement.

Optical oxygen sensors require a single-point zero-calibration. The single-point calibration is used to set the zero – this is where the optical signal varies the most, hence an accurate setup is essential if accurate measurement below  $1 \mu\text{g} \cdot \text{kg}^{-1}$  is required.

In the past months, a number of questions regarding the calibration of optical sensors have arisen with talk of "inline calibration" methods; however what sounds like nirvana comes with serious shortcomings. "Inline-calibration" in reality aligns the system with an external reference reading – applying an "offset." This does not calibrate the system within a range nor set the zero-point accurately. If a system has been correctly calibrated, this concept does however offer a method of improving the reproducibility of a system if a very reliable external reference source exists.

The big advantage of optical calibration is that no chemicals are required. The sensor can be calibrated using a pure oxygen-free gas such as nitrogen or carbon dioxide with no other liquids required for cleaning due to the electrolyte-free sensor. The only reliable calibration method remains exposing the sensor during calibration to a known reference sample to adjust the zero-point.

We recommend the use of an ultra high purity gas (99.999 % purity) as a reference zero value, which helps ensure accuracy at sub- $\mu\text{g} \cdot \text{kg}^{-1}$  measurement levels.

Figure 2 compares the maintenance, calibration, stabilization, and response time of an optical sensor with those of an amperometric sensor. This shows that the maintenance and stabilization time of an optical sensor is 82 % less than that of a typical amperometric sensor. When combined with the fact that maintenance is required 3 times less than with an

amperometric sensor, the operator workload can be reduced by 95 %. Such time and cost savings become significant within a power plant with a multitude of oxygen sensors.

This also demonstrates that optical sensor response time (post-calibration) from air to reach  $4 \mu\text{g} \cdot \text{kg}^{-1}$  is 79 % faster than that of a typical amperometric sensor, resulting in more system up-time and much lower operator intervention.

## COMPARATIVE TESTS AND INSTALLATIONS

Many different tests have been performed in power plant environments globally to demonstrate the significant benefits that can be achieved by using optical oxygen sensors when compared with amperometric sensors.

The data discussed and illustrated in this paper includes data from the following installations:

- Combined cycle power plant, 1 000 MW capacity, running an AVT water chemistry
  - Feedwater oxygen measurement; typical values in the  $0\text{--}10 \mu\text{g} \cdot \text{kg}^{-1}$  range at temperatures of  $15 \text{ }^\circ\text{C}$  –  $25 \text{ }^\circ\text{C}$ .
  - Within the AVT chemistry, carbohydrazide and ammonia were present.
  - Both the Orbisphere K1100 optical sensor and the Orbisphere A1100 amperometric sensor were installed.

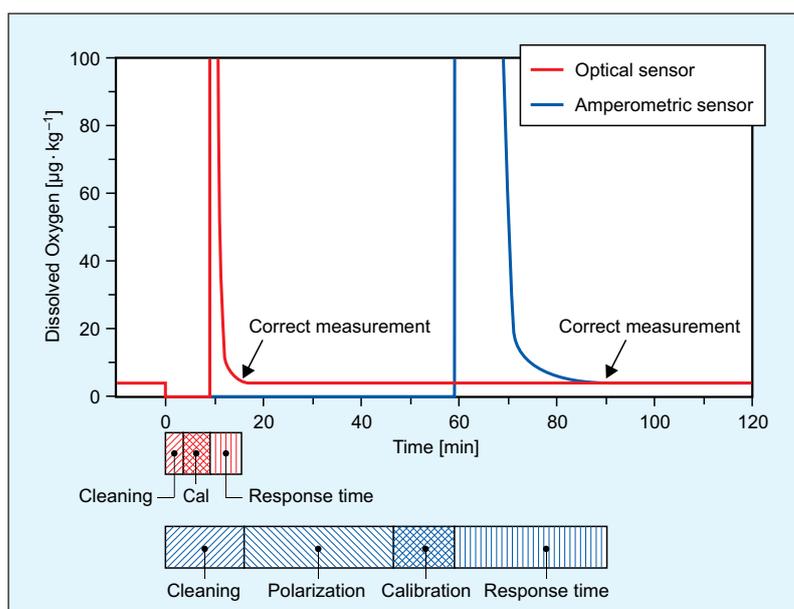


Figure 2: Maintenance, calibration, stabilization and response timeline for an optical vs. an amperometric sensor.

- BWR nuclear power plant, 355 MW capacity running hydrogen water chemistry (HWC)
  - Reactor water measurement, typical values below  $1 \mu\text{g} \cdot \text{kg}^{-1}$  during hydrogen injection (during normal operation) at temperatures of  $18 \text{ }^\circ\text{C} - 23 \text{ }^\circ\text{C}$ .
  - Hydrogen present in feedwater at  $180 \mu\text{g} \cdot \text{kg}^{-1}$ ; radiation level of approximately  $160 \mu\text{Sv} \cdot \text{h}^{-1}$ .

Power plants operating with AVT water chemistries typically require lower level and hence more accurate oxygen measurement than those running OT water chemistries. The oxygen levels commonly encountered within fossil power plants have been discussed in prior papers by Dooley and Shields [12]. Given such varying concentrations and water chemistries, a clear understanding of the factors impacting system performance is essential.

## SENSOR REPEATABILITY AND STABILITY

Oxygen levels in power plant applications and their monitoring depend heavily on the measurement point and water chemistry in question.

Whilst some amperometric sensors can measure with an accuracy of  $0.1 \mu\text{g} \cdot \text{kg}^{-1}$ , this is balanced with a number of drawbacks:

- Instability or drift between maintenance interventions;
- Effort and costs associated with minimizing errors due to drift through more regular calibration and sensor maintenance.

For this reason, it is essential to consider the oxygen levels to be measured along with the constraints of time and the confidence to be placed in a system.

Before the merits of the different technologies are discussed, it would be wise to define a number of key measures that are often overlooked by vendors:

- Repeatability  
the ability of a given sensor/system to consistently measure time and again a reference sample.
- Reproducibility  
the deviation in readings from one sensor/system to another in the same reference sample.
- Accuracy  
a measure of the trueness of a system when comparing the measured and actual values.

- Stability  
how the accuracy of a sensor/system differs over time.

These metrological terms and definitions are widely accepted [13]; however, contrary to popular belief, there is no definition of precision in the measurement of water chemistry parameters.

Given these varied definitions along with the most commonly implemented water chemistries discussed earlier, we will discuss system repeatability and stability, discussing how accurately a system can measure and also how well a system performs over time (stability), often referred to with a measure of drift.

Most systems tend to measure well after calibration. However, close to 100 % of measurements are completed when a system's longer-term performance starts to play a major role, hence the elevated importance of any oxygen system's repeatability and stability.

## Repeatability

System repeatability varies greatly based on the system in addition to the various technologies and controllers used. It is essential to note that the better the repeatability of a system, the less noisy the measurement is.

Figure 3 illustrates a comparative test completed between an Orbisphere A1100 amperometric sensor, often considered the reference for online oxygen measurement, and the Orbisphere K1100 optical sensor. This optical sensor is used in all the following tests and comparisons.

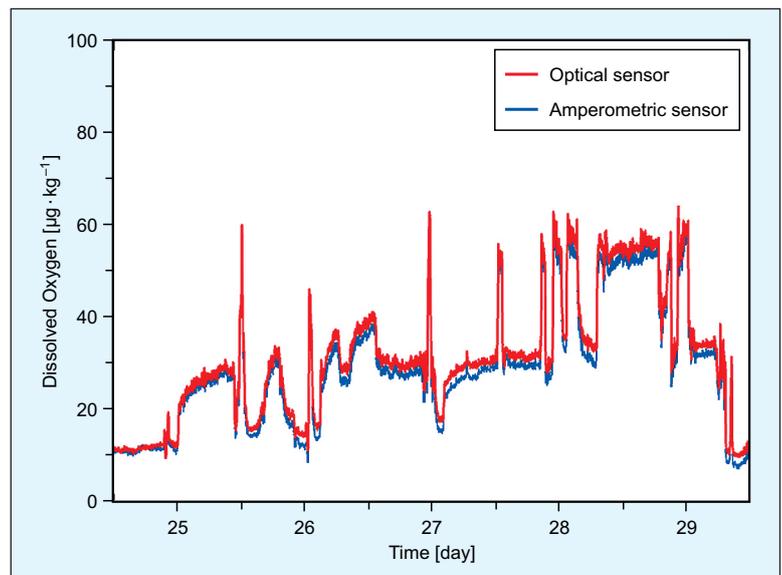


Figure 3: Comparative test of an optical and an amperometric sensor in an AVT water chemistry, boiler feedwater application.

The optical sensor is shown to measure with a repeatability ( $r_{95}$ ) of  $\pm 0.1 \mu\text{g} \cdot \text{kg}^{-1}$  at levels below  $5 \mu\text{g} \cdot \text{kg}^{-1}$ . This repeatability is comparable with the most accurate amperometric sensors available, whose repeatability ( $r_{95}$ ) of  $\pm 0.1 \mu\text{g} \cdot \text{kg}^{-1}$  is equivalent to that demonstrated by the optical sensor. This offers excellent measurement accuracy in power plant applications for OT, AVT, and chemistries applied in NPPs.

**Stability**

Sensor drift is the major cause of concern for plant operators and can result in excessive calibration and maintenance.

The stability of a system directly impacts the confidence placed in it over time – a system that drifts significantly will never be trusted as the source of information in process control. With a number of systems showing a drift of  $\pm 5\%$  [14] and up to  $\pm 2 \mu\text{g} \cdot \text{kg}^{-1}$  per week in the measured values [15], this leads to frequent operator intervention for calibration and a lack of trust in the system. Such drift of up to  $\pm 2 \mu\text{g} \cdot \text{kg}^{-1}$  per week in applications below  $5 \mu\text{g} \cdot \text{kg}^{-1}$  is not acceptable for many operators in fossil power plants.

With the stability or drift of a system playing such an important role in measurement during the time between calibrations, it is really the overlying factor in all oxygen measurement systems. Figure 4 illustrates the impact of an amperometric sensor drifting  $\pm 2 \mu\text{g} \cdot \text{kg}^{-1}$  per week and the frequency of calibration required for such systems when compared to both a typical amperometric system and also the optical sensor if recalibration is required when drift amounts to  $2 \mu\text{g} \cdot \text{kg}^{-1}$ .

Amperometric sensors suffer drift when the electrolyte ages (has been consumed by the oxygen measured), resulting in the sensor becoming less responsive. When higher oxygen levels are measured, for example, as part of plant start-up or shutdown, this drift becomes even more pronounced – all this at the time when measurements should be the most accurate as equipment is brought online and high oxygen levels are to be expected. Protecting capital equipment here is key.

With optical technology, long-term aging of the luminescent spot causes upwards drift and results in a rise in measured values. The technology used within the optical system results in a far superior stability and an interval between calibrations of 12 months. So as the time between calibrations increases and the variability from stability and drift play an increased role, optical systems offer an additional level of protection and reassurance.

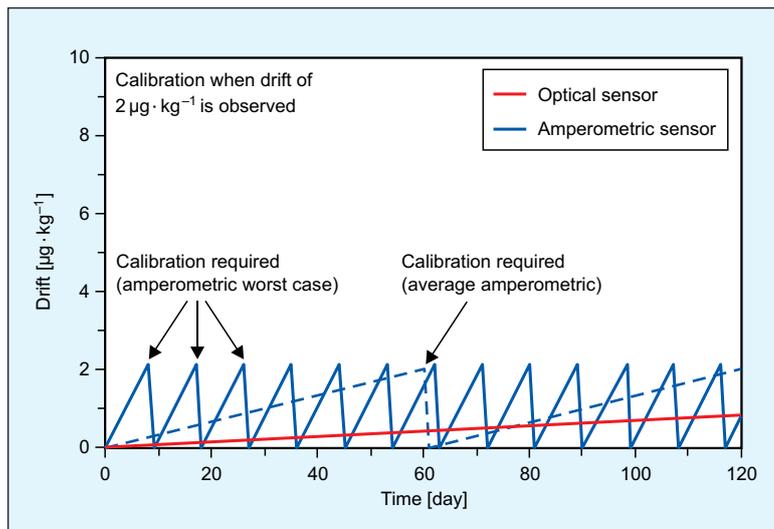


Figure 4: Comparison of the drift of different sensors and its impact on calibration requirements when measuring at  $4 \mu\text{g} \cdot \text{kg}^{-1}$  levels.

**SYSTEM PERFORMANCE IN HYDROGEN RICH SAMPLES**

As previously mentioned, NPP measurements in the PWR primary cycle, where highly precise readings are required, can be more troublesome for amperometric sensors. Often primary cycle chemistries include high levels of hydrogen in the measurement sample – amperometric sensors can experience a negative offset from high levels of hydrogen, at times up to  $10 \mu\text{g} \cdot \text{kg}^{-1}$ . Whilst systems do exist to compensate for this offset [16], accurate oxygen readings are critical to plant operation in both HWC and normal water chemistry plants [17].

The advantage of optical technology in NPP water chemistries is that optical sensors are unaffected by high levels of hydrogen in the measurement sample – when measuring low levels of oxygen, this is a critical feature.

Table 1 compares tests of the Orbisphere K1200 optical sensor (a derivative of the K1100 for radioactive applications) to values measured by an amperometric sensor

	Dissolved Oxygen Readings [ $\mu\text{g} \cdot \text{kg}^{-1}$ ]	
	Amperometric Sensor	Optical Sensor
Cycle 1	-3.2	1
Cycle 2	-3.2	0.2
Cycle 3	-3.5	0.3
Cycle 4	-3.5	0.9

Table 1: Comparison of the Orbisphere K1200 optical sensor and an amperometric sensor in PWR primary conditions.

without any hydrogen compensation features in primary cycle PWR water by an independent testing group [18]. A hydrogen pressure of  $\sim 2.3$  bar (STP) was set with dissolved hydrogen concentrations of  $3.36 \text{ mg} \cdot \text{kg}^{-1}$ . Values illustrated show a mean result over 5 measurement points and 4 measurement cycles.

This comparison shows the negative offset experienced by amperometric sensors in the presence of hydrogen whilst the optical sensor remains unaffected by high levels of dissolved hydrogen.

Figure 5 illustrates the performance of the optical system online in HWC nuclear chemistry when compared with a reference amperometric system configured with hydrogen compensation. It can be seen that the repeatability of the optical system within an HWC chemistry at oxygen levels  $< 0.5 \text{ } \mu\text{g} \cdot \text{kg}^{-1}$  is excellent and is unaffected by the presence of hydrogen.

Figure 6 shows the optical sensor in a reactor water application as the oxygen level drops and then stabilizes at a  $0.4 \text{ } \mu\text{g} \cdot \text{kg}^{-1}$  level. Again, the optical sensor shows a repeatability  $< 0.1 \text{ } \mu\text{g} \cdot \text{kg}^{-1}$ , offering excellent consistency at very low oxygen levels.

### SYSTEM PERFORMANCE UNDER THE INFLUENCE OF FLOW VARIATIONS

Within any power plant, the performance of any sampling system plays a role in the accuracy of most analytical systems. When flow is reduced below recommended levels, this can impact the accuracy of the measurement systems. Figure 7 shows how the performance of the optical sensor is independent of flow when compared with an amperometric sensor.

The optical system only requires enough flow to provide a fresh sample whereas amperometric sensors have a range and minimal flow levels below which measurement errors could be encountered. For example, a flow rate that is 30 % lower than a recommended minimum would likely result in an error of up to 10 %.

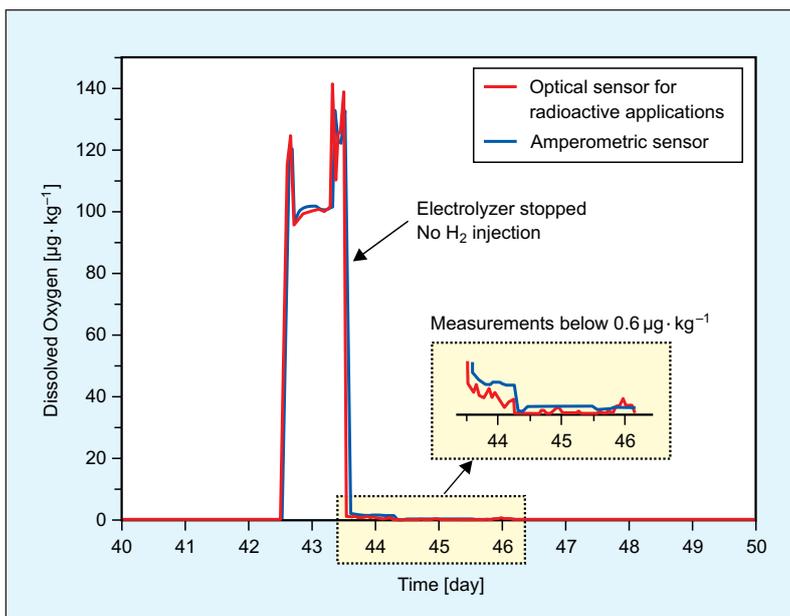


Figure 5: Comparison of the optical sensor for radioactive applications with an amperometric sensor in an HWC nuclear chemistry.

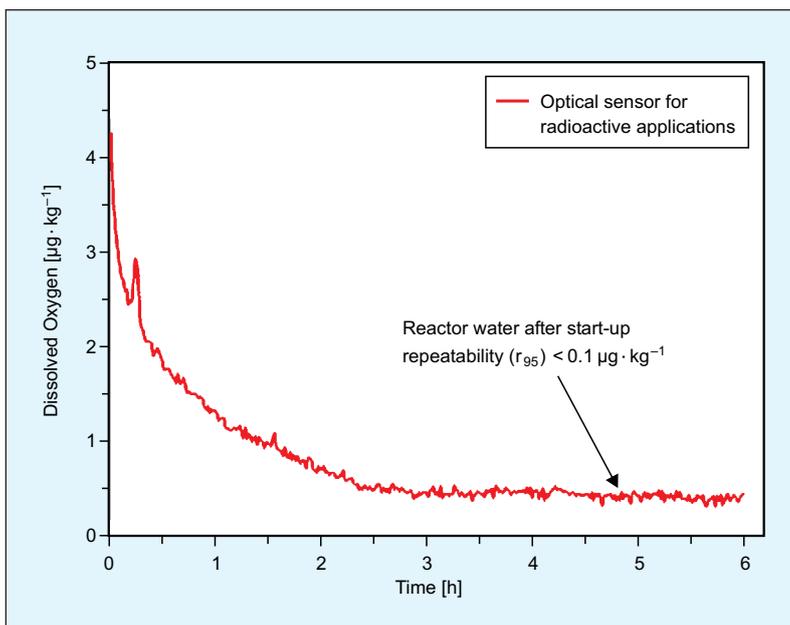


Figure 6: Optical sensor in a BWR reactor water application after start-up.

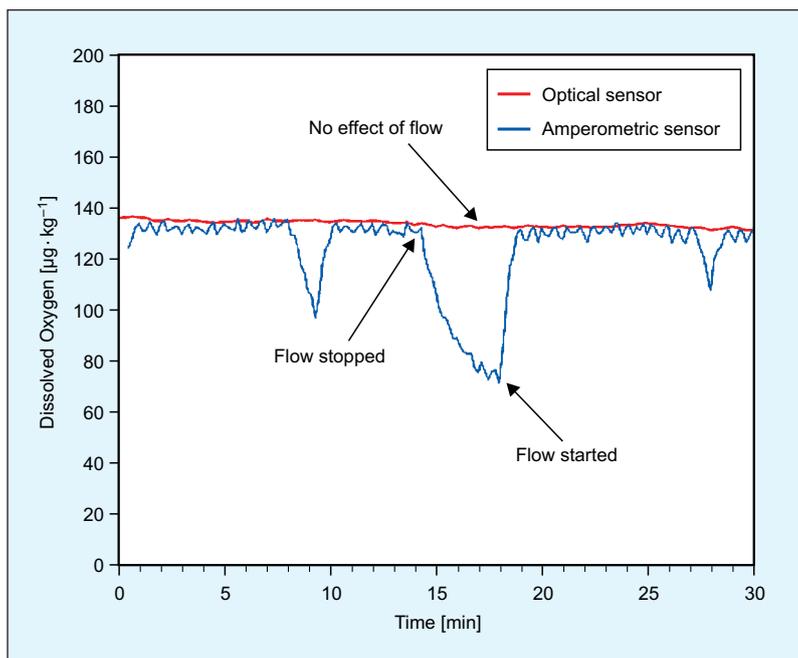


Figure 7:  
Comparison of an amperometric sensor with the optical sensor under variations in flow.

## CONCLUSIONS

We have compared and discussed the performance of both optical and amperometric oxygen sensors in fossil and nuclear power plant applications.

The measurement and control of dissolved oxygen levels in power plant chemistry has never been so critical. With the number of qualified maintenance engineers continually declining, and greater economic pressure on plant operators to protect and maximize the useable life of capital equipment, the time available to maintain instrumentation is of critical importance.

We have shown through comparative tests that the repeatability of the Orbisphere K1100 optical sensor discussed here is comparable with that of the amperometric sensor when used in power and industrial water applications, especially at levels below  $5 \mu\text{g} \cdot \text{kg}^{-1}$ . In terms of stability, the optical sensor has proven to be far superior to amperometric sensors with a calibration interval of 12 months with no intermediate intervention required during this period.

In the comparative tests completed, the optical sensor has proven its accuracy to be independent of flow variations and the Orbisphere K1200 optical sensor for radioactive applications showed no interference from elevated hydrogen concentrations – both these points provide additional confidence in measured values.

In terms of response time and maintenance efforts, the response time (post-calibration) of the optical sensor discussed here to reach  $4 \mu\text{g} \cdot \text{kg}^{-1}$  was 79 % faster than that of the fastest amperometric sensor and the reduction in calibration and maintenance efforts over the best amperometric sensors amounts to a 95 % reduction in maintenance efforts.

The optical sensor discussed here and the technical advances it brings to customers offer the most time and cost effective solution for accurate oxygen monitoring available. With a demonstrated repeatability of  $\pm 0.1 \mu\text{g} \cdot \text{kg}^{-1}$  and the possibility to measure continuously over a 12-month period without any calibration or user intervention, this optical sensor system sets a new standard for oxygen measurement in power plants.

## REFERENCES

- [1] Dooley, B., Shields, K., *PowerPlant Chemistry* **2004**, 6(3), 153.
- [2] McInnes, D., *PowerPlant Chemistry* **2006**, 8(5), 298.
- [3] Smith, R., *Wall Street Journal*, **2010**, 14/01.
- [4] *HACH LDO® Dissolved Oxygen Probe Data Sheet, 2007*. Hach Company, Loveland, CO, U.S.A. Downloadable at [http://www.hach.com/hc/view.file.details.invoker/View=FL2455/NewLinkLabel=LDO+Dissolved+Oxygen+Probe+Data+Sheet+\(lit2455\)/SESSIONIDIAxpjeU9UZzNOVGMzTkRjNEptZDFaWE4wV1UxTVVGU XhNZz09Qg==l](http://www.hach.com/hc/view.file.details.invoker/View=FL2455/NewLinkLabel=LDO+Dissolved+Oxygen+Probe+Data+Sheet+(lit2455)/SESSIONIDIAxpjeU9UZzNOVGMzTkRjNEptZDFaWE4wV1UxTVVGU XhNZz09Qg==l).
- [5] *OPTI® CCA Blood Gas and Electrolyte Analyzer, 2008*. OPTI Medical Systems, Atlanta, GA, U.S.A. Downloadable at [http://www.optimedical.com/products/opti/opti\\_cca\\_over.htm](http://www.optimedical.com/products/opti/opti_cca_over.htm).
- [6] Lindblom, T., *Qualitative Comparison of Optical and Amperometric Sensors for Measuring Dissolved Oxygen in Bioreactors, 2009* Linköping University, Sweden.
- [7] Pütz, P., *Determination of Oxygen in Wine, 2008*. Downloadable at <http://www.aguafrica.co.za/PDF/HQd.pdf>.

- [8] *Case History: Bristol-Myers Squibb/Hach Process Luminescence DO*, **2004**. Downloadable at [http://www.hach.com/hc/view.file.invoker/5790000/View=FILCAT\\_APPLICATION\\_CASE\\_HISTORY/NewLinkLabel=Application+Case+History](http://www.hach.com/hc/view.file.invoker/5790000/View=FILCAT_APPLICATION_CASE_HISTORY/NewLinkLabel=Application+Case+History).
- [9] *Standard Test Method for Dissolved Oxygen in Water*, **2009**. ASTM International, West Conshohocken, PA, U.S.A., ASTM D 888 - 09.
- [10] Dunand, F., Ledermann, N., Hediger, S., *PowerPlant Chemistry* **2006**, 8(10), 603.
- [11] Dunand, F., Guillou, P., *Proc., API PowerChem 2008 : Power Station Chemistry Conference*, **2008** (Twin Waters, Queensland, Australia).
- [12] Dooley, B., Shields, K., *PowerPlant Chemistry* **2004**, 6(3), 153.
- [13] *International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM)*, **2007**. International Organisation for Standardisation, Geneva, Switzerland, ISO/IEC Guide 99:2007.
- [14] *Low and High Level Dissolved Oxygen Monitor Model 9437*, **2006**. ABB Limited, Stonehouse (Gloucestershire), United Kingdom, Data Sheet SS/9437\_7.
- [15] *Dissolved Oxygen Analyzer Aqualyzer® 9062*. Waltron LLC, Whitehouse, NJ, U.S.A. Downloadable at [http://www.waltron.net/dissolved\\_oxygen\\_analyzer\\_9062.asp](http://www.waltron.net/dissolved_oxygen_analyzer_9062.asp).
- [16] *Orbisphere 512 Oxygen-Hydrogen Controller*, **2009**. Hach-Lange, Geneva, Switzerland. Downloadable at [http://shop.hach-lange.com/shop/action\\_q/download%3Bdocument/DOK\\_ID/14787466/type/pdf/lkz/II/spkz/en/TOKEN/KzLLWyA7MB7BhShL-JG1gbkAsy0/M/g2Jfhg](http://shop.hach-lange.com/shop/action_q/download%3Bdocument/DOK_ID/14787466/type/pdf/lkz/II/spkz/en/TOKEN/KzLLWyA7MB7BhShL-JG1gbkAsy0/M/g2Jfhg).
- [17] Böttcher, F., *Proc., International Conference Instrumentation for Power Plant Chemistry*, **2006** (Zurich, Switzerland). PowerPlant Chemistry GmbH, Neulussheim, Germany.
- [18] Auener, Ch. (Serco Technical and Assurance Services, Risley, United Kingdom), **2009**.

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**Frank Dunand** (M.S., Chemistry, University of Fribourg, Ph.D., Chemistry, Swiss Federal Institute of Technology, both in Switzerland) joined Orbisphere in 2002 as a product manager, and was then promoted to senior product manager heading the team managing all Orbisphere and Polymetron products. He currently holds global responsibility for product innovation at the Hach-Lange facility in Geneva, Switzerland. Frank Dunand is the author of 16 technical papers in the analytical chemistry field.

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