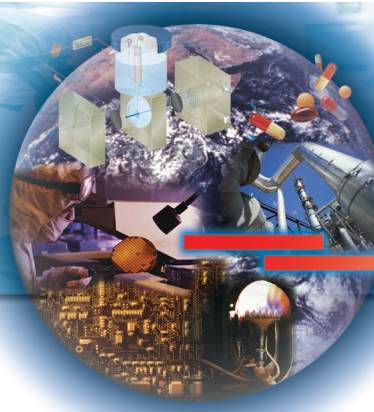
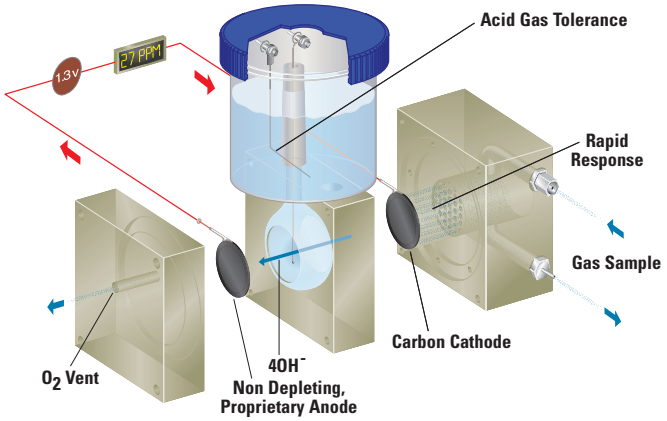
Technical Bulletin: The $\mathcal{E}$-Sensor



Delta F has been the technology leader in oxygen analysis for the past 15 years with its non-depleting electrochemical sensor technology. Over that time, the standard coulometric sensor has been optimized, the NanoTrace and M-Sensors have been developed and introduced, and all have attained unparalleled performance and reliability in their respective markets, which is an enviable situation from a competitive standpoint. Dramatically improving upon that would be a real challenge and one that none of our competitors were up to as Delta F's sensors have withstood the test of time. In the end, it took the best to beat the best... as Delta F now introduces the new enhanced performance $\mathcal{E}$-Sensor. A brief review of the sensor history leading to the development of the $\mathcal{E}$-Sensor will provide a basis for, and illustration of the significance of this breakthrough.

Standard Coulometric Sensor

The standard Delta F non-depleting electrochemical sensor of today is fundamentally the sensor that the company was founded on. Under the auspices of our ISO9001 Quality Program, a number of packaging and geometry changes have been implemented over the years to improve productivity and reliability. Furthermore, various controls were implemented and numerous processes were optimized to improve performance consistency and reliability. The net result of these continuous improvements was to drive sensor production yield to 99% with unparalleled reliability. Reliability was so good that it allowed us to increase the standard sensor warrantee to an industry-leading 100% coverage for 5 years. Performance however, while very good, has remained largely unchanged over the past 15 years as it is tied directly to the electrode system, which has been unchanged since initial development in the early 1970's.



$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \text{ (cathode)}$$

$$4OH^- \rightarrow O_2 + 2H_2O + 4e^- \text{ (anode)}$$

NanoTrace Sensor

The NanoTrace sensor was developed and introduced in 1994 to serve the demanding sub-ppb ultratrace requirements of the semiconductor market. At the time, Delta F leapfrogged the competition by offering a 200 ppt low detection limit (LDL) and quickly won the market by consistently delivering extremely dependable and reliable instruments that met or exceeded their specifications; something that industry had a tremendous need for but had not been accustomed to. In 1998, recognizing the semiconductor industry's continued trend toward lower contaminant levels, and in anticipation of the industry's instrumentation requirements, Delta F introduced the NanoTrace II with a 75 ppt LDL. This product was equally successful and to this day we enjoy a 95%+ UltraTrace market share. Both of these sensors employ proprietary and patented features which provide exceptional low range measurement. Unfortunately, they are restricted to the low range by their nature.

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NanoTrace and NanoTrace II sensors are differentiated through performance selection and in both cases, the performance is largely what it has been for the past 12 and 8 years respectively.

M-Sensor

The M-Sensor was developed in 1998 in recognition of the need for reliable ppb level process oxygen monitoring for various applications such as rapid thermal processing and high purity air separation where trends were continuing toward more stringent gas purity levels. By incorporating concepts and features of the NanoTrace sensor into the standard coulometric sensor (to create the M-Sensor), we significantly improved sensitivity, speed of response, accuracy, and stability. The M-Sensor enabled users to accurately and reliably monitor and maintain high purity gases in many critical applications. However, its use is limited to the 0-50ppm range of operation as it cannot tolerate the high current levels generated in higher trace and percent level sensors. Further, it is unable to withstand the higher contaminant and acid gas levels present in many process applications at those levels. These constraints are inherent in the fundamental design of the M-Sensor and have thus limited the improved performance to the low trace applications.

ℰ-Sensor

While all Delta F non-depleting electrochemical sensors deliver excellent performance and reliability, the common theme with each of the sensors is that they were at their performance limits. Over the years they had been optimized to the maximum extent possible and further improvement was constrained by their very design. To advance the technology further required extensive research and engineering to determine and address root causes limiting the various performance attributes. This entailed studying and analyzing the design and construction of the sensor assembly all the way down to and including the electrolyte formulation, formulation and fabrication of the electrode systems, the raw materials used, and pre- and post-processing of them.

Three years and several million dollars later, this tremendous challenge gave way to a breakthrough in oxygen sensing with the debut of Delta F's enhanced performance ℰ-Sensor. The results have surpassed all objectives and expectations. As has always been the case, details of the Delta F ℰ-Sensor technology are a trade secret, however generally speaking we have:

- Characterization and identification of optimum materials of construction for the cathode electrode system
- Development of a new cathode electrode system fabrication process
- Elimination of impurities in the raw materials of the electrode systems, processing of the electrodes, and the electrolyte
- Development of a proprietary high purity anode
- Development of new sensor assembly and conditioning processes
- Development of new electrolyte formulations and high purity replenishment solution

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Collectively, these changes have enabled extension of the M-Sensor design concept to cover the entire range of our product offerings for the process oxygen monitoring market; that is from 0-50ppm to 0-25%. Further, these changes have delivered an array of performance improvements including:

- Improved purge-down time (reference figure 1)
- Improved upset recovery (reference figure 2)
- Elimination of need for Quick Start
- Improved speed of response (reference figure 3)
- Extended range of operation/ low end resolution (reference figure 4)
- Improved linearity and accuracy (reference figure 5)
- Improved baseline stability
- Improved temperature stability (reference figure 6)
- 25 - 500% Improvement in hardiness/ acid gas tolerance
- 50% Reduction in fluid-loss and accompanying maintenance

With respect to the NanoTrace, many of these improvements are also realized including:

- Improved purge-down time
- Improved upset recovery
- Improved speed of response
- Improved baseline stability
- Improved temperature stability
- Improved hardiness/ acid gas tolerance
- 50% Reduction in fluid-loss and accompanying maintenance

All Delta F non-depleting electrochemical sensors have been very successful in their respective products and markets. The objective in developing the $\mathcal{E}$-Sensor was to break through the performance limitations inherent in our contemporary electrochemical sensors and the motivation was to maximize price-performance of our oxygen analyzers in doing so. This advancement further asserts our commitment to maintain technological leadership. Incorporation of the $\mathcal{E}$-Sensor in all of the Delta F oxygen analyzers will sustain our best in class performance well into the future.

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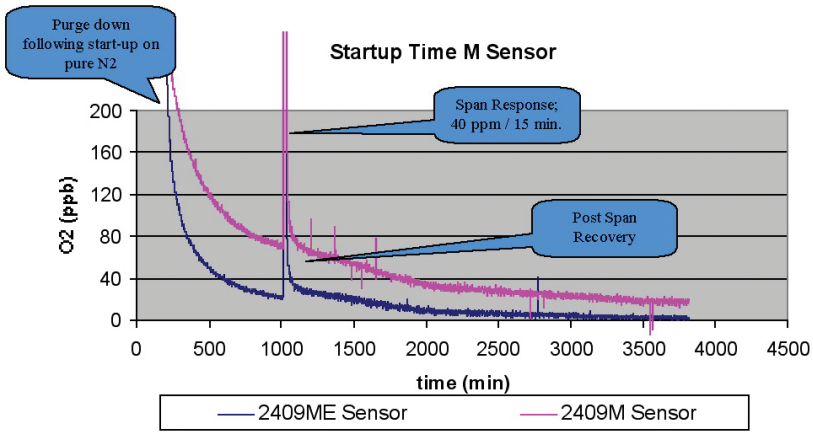
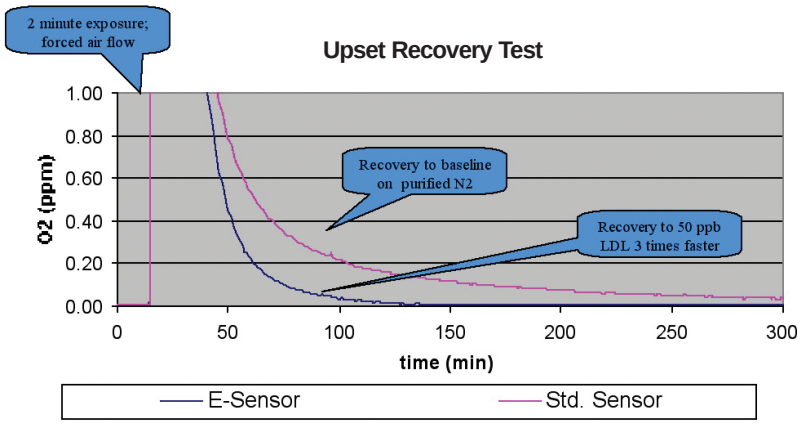
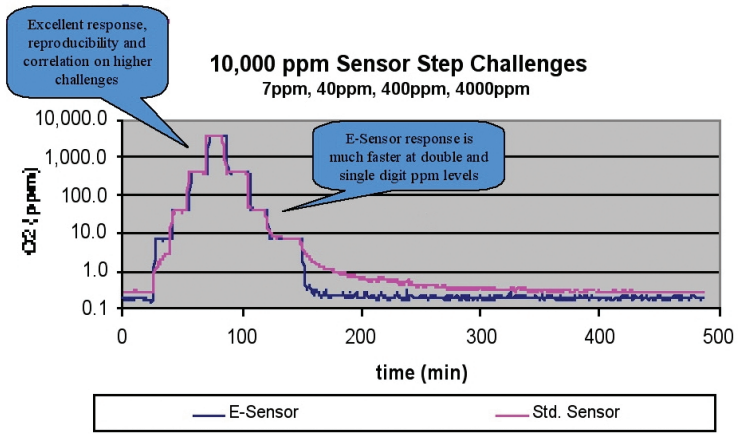
Improved Purge-Down Time (figure 1)



Improved Upset Recovery (figure 2)



Improved Speed of Response (figure 3)



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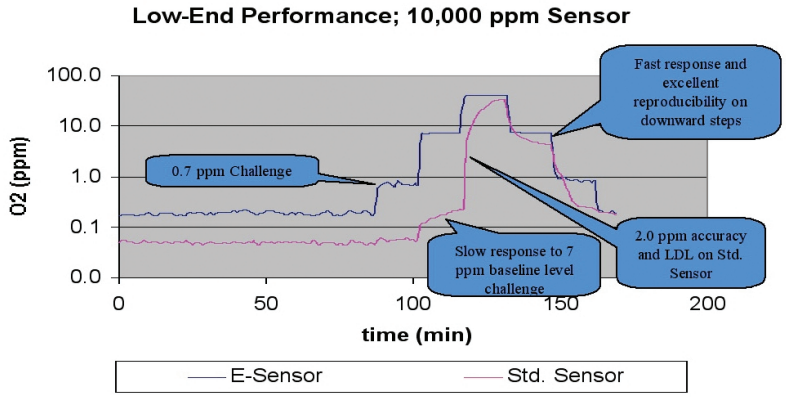
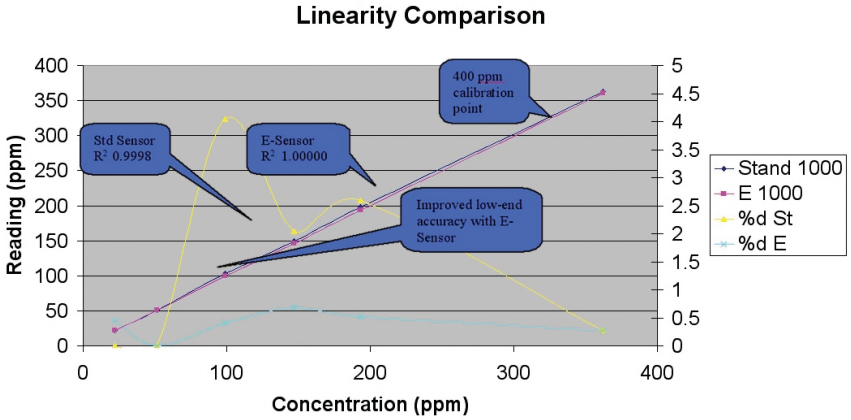
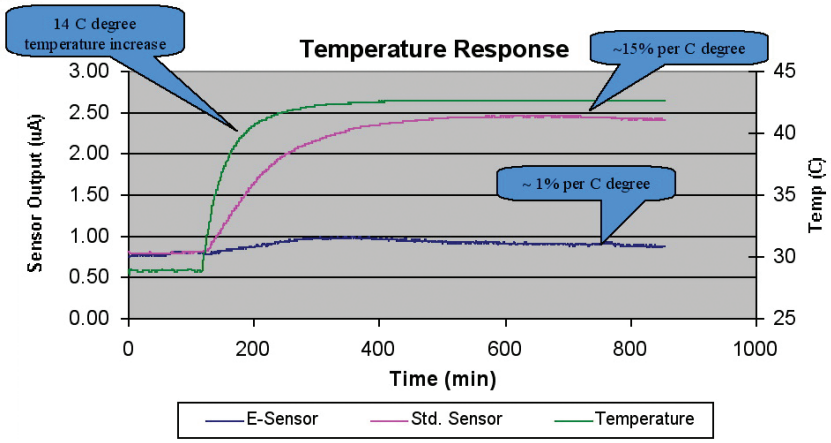
Extended Range of Operation/Low End Resolution (figure 4)



Improved Linearity and Accuracy (figure 5)



Improved Temperature Stability (figure 6)



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