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Non-Intrusive Sensor for Gas Fill Verification of Insulated Glass Windows

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ABSTRACT

A sensor capable of measuring the amount of oxygen (an unwanted component that is only present because of improper filling or seal failure) within an argon-filled insulated glass window has been designed, built and successfully tested. It operates by using the optical absorption of oxygen in the atmospheric A-band centered at 762 nm. Light emitted by an argon-filled surface glow discharge lamp is Zeeman-tuned on and off an oxygen absorption line using an AC-modulated electromagnet. In the presence of oxygen, the change in the measured intensity of the lamp, obtained using standard demodulation techniques, is proportional to the oxygen column density. Measurements using an industry-standard insulated glass window indicate that the sensor can measure the amount of oxygen in a nominally argon-filled IG window (with a window gap of 10 mm) with a precision of 0.50% oxygen using a 16 second integration time. This level of precision is well within the limits required by the IG window manufacturing industry for proper monitoring of newly manufactured window units.

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EXECUTIVE SUMMARY

The overall objective of the proposed project was the invention and development of a sensor which can verify the proper gas filling of Insulated Glass (IG) windows in a non-intrusive and non-destructive manner. It also addresses the need for a field-based sensor that will determine if window seal damage has occurred. This sensor can be adapted for production quality control (testing for complete substitution of air by argon or other such low thermal conductivity gas), evaluating inventory units, and most importantly, used to test IG window integrity in the field.

Studies indicate that fully half of all new IG windows being produced do not meet their specified argon fill levels resulting in a significant loss of energy reduction potential for gas filled insulated glass windows. That loss is estimated, by the year 2010, to total .035 quad of energy yearly at a cost of over \$200 million just in the United States alone. This lost energy reduction also results in the emission of a half a metric ton of carbon into the atmosphere resulting in increased global warming potential. Increased NO_x and SO_x (oxides of nitrogen and sulfur) levels caused by the extra power generation also contribute to air pollution. Because of legal liability issue, the industry may have to drop the entire practice of gas filling. If so, the energy losses and concomitant increase in carbon emission levels would increase by a factor of four. There is also a significant failure rate for windows already installed in residential and commercial buildings. A sensor that could detect window seal failure *in situ* and concomitant loss of gas fill could also result in significant energy savings for the United States.

At present, there is no accepted non-destructive technique for actually determining the displacement of air by argon (or other fill gas) in the window gap during the filling process. Once the windows are sealed, grab samples of the gas fill are obtained using a syringe from a small sample size of windows for off-line analysis. In practice, window manufacturers typically determine a proper fill time by measuring the oxygen content of the exhaust gas from test windows being filled and assume that these parameters apply to a production line environment. Use of muntins (the vertical and horizontal bars used to build a multi-lite sash) to create a grid-like appearance further complicates matters. It is difficult to remove air from these tubular structures. In addition, the testing of windows for subsequent seal failure is hampered by the inability to establish how much air has penetrated into the argon-filled window.

A sensor capable of measuring the amount of oxygen (an unwanted component that is only present because of improper filling or seal failure) within an argon-filled insulated glass window has been designed, built and successfully tested. Known as the OWL-IG (Optical WaveLength-

Insulated Glass), it operates by using the optical absorption of oxygen in the atmospheric A-band centered at 762 nm. Light emitted by an argon-filled surface glow discharge lamp is Zeeman-tuned on and off an oxygen absorption line using an AC-modulated electromagnet. In the presence of oxygen, the change in the measured intensity of the lamp, obtained using standard demodulation techniques, is proportional to the oxygen column density. The OWL-IG operates by measuring the amount of oxygen within its optical beam path with and without the presence of the IG window. The difference, after correction for pressure, temperature, humidity and the dimensions of the window, provides the oxygen concentration within the window cavity.

Measurements using an industry-standard insulated glass window indicate that the OWL-IG can measure the concentration of oxygen in a nominally argon-filled IG window (with a window gap of 10 mm) with a precision of 0.50% oxygen using a 16 second integration time. This level of precision is within the limits required by the IG window manufacturing industry for proper monitoring of newly manufactured window units.

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1. INTRODUCTION

1.1 Problem Definition

Leak detection in argon-filled insulated glass windows has become an increasing concern for the window manufacturing industry.[1] Once a double-paned window has been purged of air and filled with argon, no further checks on the proper filling or seal integrity of the window (at least with respect to the out-leakage of argon and/or in-leakage of air) are made before either shipping or installation. In fact, the only sign of subsequent window seal failure is that water vapor condensation occurs, an event that takes place only after the desiccant included in the window design has become saturated. While such condensation presents aesthetic problems, it also indicates that the argon fill has been compromised and that the window probably does not meet regulatory criteria (mandatory or voluntary) for insulating properties.

This project involved a collaboration between Aerodyne Research, Inc., a small business which focuses on trace gas detection sensor development, and FDR Design Inc., a small business which is a major seller in the U.S. of gas filling equipment to the fenestration industry. Aerodyne Research was responsible for all sensor development and testing. FDR Design provided test equipment and a great deal of consulting time concerning the IG window industry practices and concerns.

The basis for the OWL-IG (Optical WaveLength-Insulated Glass) sensor is a patented technology which provides for the detection of oxygen (a major component of air) by means of measurement of optical absorption of near visible light.[2] This novel monitor utilizes optical absorption of an emission line emanating from a simple gas discharge lamp that coincides with a feature in the oxygen absorption band in the near visible (~ 760 nm). (We note that neither nitrogen nor argon can be readily detected using optical absorption spectroscopy. This technique would require the use of vacuum ultraviolet light below 150 nm, wavelengths which are not compatible with window glass.) Detection using light of this wavelength permits the use of optical fibers to link a light source/detector module with a remote measurement module. Furthermore, the measurement technique can be made non-invasive and non-contact - an advantage over existing oxygen monitoring techniques such as solid state sensors (which also require elevated temperatures), paramagnetic sensors and electrochemical cells. Although there is a tradeoff between sensitivity and time response, a reasonable goal is a sensitivity of 2% oxygen (as a component of air) with an integration time of 1 minute. This corresponds to a gas fill level of 90%, a level required to ensure reaching the highest thermal performance.

The conservation of energy resources has become a major goal of national energy policy ever since the energy crisis of the late 1970's. The Environmental Protection Agency has created a voluntary Energy Star labeling system in order to enable consumers to identify energy efficient windows and other products. The standards for obtaining the Energy Star label for the northern tier of the United States are quite high and pose a challenge to window manufacturers. In order to meet this need, the modern IG window has evolved into a unit comprising at least two panes of glass, a spacer intended to control the gap between the panes, a low emissivity coating on one of the panes, and desiccant material intended to absorb any moisture which enters the gap. This 'sandwich' is then held together by an adhesive which also acts as a sealant. In order to meet the Energy Star standards, manufacturers must also limit the convective currents within the gap which serve to increase heat conductance through the window. The most common approach to this problem is to fill the gap with a gas that has a lower thermal conductivity than air; argon, an inert, colorless, odorless, non-toxic, naturally occurring gas, is generally used to fill the gap. Krypton, a gas similar to argon which offers a somewhat better but much more expensive alternative, is also occasionally used in this capacity.

There is no accepted non-destructive technique for actually determining the displacement of air by argon (or other fill gas) in the window gap. Once the windows are sealed, grab samples of the gas fill are obtained using a syringe from a small sample size of windows for off-line analysis. In practice, window manufacturers typically determine a proper fill time by measuring the oxygen content of the exhaust gas from test windows being filled and assume that these parameters apply to a production line environment. Use of muntins (the vertical and horizontal bars used to build a multi-lite sash) to create a grid-like appearance further complicates matters.

Studies presented at the SIGMA 2000 meeting (conducted by IGMAC and Cardinal IG) indicate that fully half of all new IG windows being produced might not meet their specified argon fill levels! This circumstance leads to energy losses which total 0.035 quads annually. This set of circumstances has also created a serious consumer liability issue. Window manufacturers advertise the use of gas filling as an energy-saving measure for which they charge the customer an added fee. A major window manufacturer paid several million dollars to settle a class action suit which concerned the argon fill levels of IG windows that were being sold. This company suspended production of all gas-filled window for a number of months for fear of facing additional lawsuits. Without a means of certifying the level of argon fill, IG window manufacturers face an uncertain future in terms of legal liability. If the practice of argon filling of IG windows is suspended, energy losses will increase by a factor of four over that value quoted above.

In addition, failures in the installed base of IG windows also presents a liability issue to the IG window manufacturing industry. A common complaint among consumers is the presence of ‘fogging’ in windows before the end of the warranty period (typically 10-20 years). This condition is caused by the diffusion of water vapor into the window gap due to seal failure. Significant argon out-diffusion and air in-diffusion has occurred by this point, although there is no way to currently measure this process. The oxygen sensor described herein allows both window manufacturers and homeowners to determine if seal failure has occurred in a fast, non-invasive, nondestructive way.

1.2 State of Current Sensor Technology

A number of approaches have been suggested and tried as solutions to this issue.[1] Until recently, there has been only one technique currently available that claims to accurately measure the presence of air in the gap between IG windows: Raman scattering. Developed by Cardinal IG, this technique requires a powerful laser, mechanically stable optical bench, and constant reference to known standards. It relies on the fact that both nitrogen and oxygen, when irradiated by a laser at one single wavelength, will produce scattered light that differs in wavelength from the laser light by an amount that is characteristic of the molecule itself. It is certainly not amenable to the development of a portable sensor and is quite expensive to buy, operate and maintain. There are also safety issues concerning the use of high power lasers. Thus, it is suitable for laboratory use by a trained technician but not for the production or field environment. In conclusion, as of now, there are no generally accepted techniques for verifying proper IG window gas fill and the maintenance of seal integrity.[1]

We were also aware at the beginning of the program of two other approaches that had been proposed to solve this problem.[3,3a] The first involves an acoustic approach to measuring gas properties. This includes a time-of-flight technique which relies on the fact that gases of different densities will cause the speed of sound to change. Unfortunately, interpretation of the data is compromised by the production of multiple reflections off of the window panes; in any case, the technique is most sensitive to the presence of heavy gases such as sulfur hexafluoride and not terribly well suited for light gases such as argon, oxygen and nitrogen. The equipment needed to measure this effect accurately is also quite expensive. Similar problems apply to the use of thermal conductivity measurements through the window gap.

The second technique is voltage break down measurement. If a sufficiently high voltage (8-15 kV) is applied to the window, a spark between the panes will be produced. The voltage at which this breakdown occurs is a function of the gas fill in the window. The problem here is that the value

of this breakdown voltage is also sensitive to the presence of coatings (or contaminants) on the windows as well as the width of the gap. A commercial version of this technique (called KONAR) is apparently being developed. It has also been suggested that the color of the gas produced in the spark would provide usable information.

However, in the past two years, a technique developed by a Finnish company, SparkLike, has been successfully used in detecting the fraction of argon in the window gas fill: spark-induced breakdown spectroscopy.[4] However, this approach has several drawbacks, the most significant being an inability to accurately measure argon fill fractions below 80% (a significant issue for windows utilizing gas fills that are not 100% argon) and the propensity to damage the various coatings applied to modern insulated glass windows. Another drawback is that a sensor unit must be laboriously recalibrated for variations in the physical dimensions of the window being interrogated and does not, as yet, work with any other window gas fill besides argon. We describe here an approach based on the detection of oxygen within the window cavity using spectroscopic techniques that provides a non-contact means of detecting improper filling or loss of seal integrity. Furthermore, calibration can be maintained over a wide range of window dimensions without significant loss of accuracy. Calibration is also independent of the fill gas composition.

1.3 Approach

While air is generally thought to be transparent to visible and near-visible light, it is not completely so. This oxygen monitor takes advantage of the existence of oxygen's optical absorption lines in the 760 nm wavelength ($13,150\text{ cm}^{-1}$ frequency) spectral region, commonly known as the atmospheric A band ($X^3\Sigma_g^- \leftarrow b^1\Sigma_g^+$). The absorption of light at a discrete wavelength, produced by an incoherent light source, specifically an argon discharge lamp, by one of the stronger lines in this band, is used to measure the oxygen concentration along a path of several centimeters length inside of the window.[2] While the approach is straightforward, the fact that oxygen is a weak absorber requires us to measure changes in differential absorptions as little as 1 part in 10^5 and provides considerable experimental difficulties.

The detection scheme is similar in many respects to that employed by us previously to detect water vapor, although it differs in several significant details.[5-7] The lamp emission of interest is the neutral argon line at 763.7 nm wavelength ($13,093.79\text{ cm}^{-1}$). [8] This line is known to be close to, but not coincident with, a strong oxygen absorption line (P9Q8) at $13,093.65\text{ cm}^{-1}$; this line is one of the strongest spectral features in the atmospheric oxygen A-band. [9,10] When

the emission line is Zeeman-split by a longitudinal DC magnetic field of the proper strength, it is divided into one component that is strongly absorbed by the oxygen line, and a second component that is not absorbed.[11] **Figure 1** presents a detailed simulation of the relevant spectral profiles of the oxygen absorption line at an ambient pressure of 1.0 atmosphere and the split emission lines in a DC magnetic field of ~ 1700 Gauss. As can be seen, Zeeman splitting of the emission line produces two components of orthogonal circular polarizations, one downshifted so as to overlap the maximum of the oxygen absorption line, and one shifted to sufficiently higher frequency so as to ensure no absorption. If one can subsequently distinguish each of the wavelength components using, for example, a polarization selection scheme employed for the water vapor sensor, oxygen concentrations can be obtained by a differential absorption measurement. This differential absorption scheme, however, requires the use of comparatively expensive components and the use of a heavy permanent magnet.

Alternatively, if one employs an AC magnetic field of proper strength instead of a fixed DC magnet, the frequency of the lamp emission can be swept over a range encompassing the frequencies ν_1 and ν_2 (or greater if desired). The presence of any oxygen in the beam path will thus produce an intensity-modulated signal that follows that AC magnetic field strength. It is this approach that will be employed in this sensor. The following discussion will describe the key elements in detail as well as the actual experimental setup used to measure oxygen concentrations within double-paned insulated glass windows.

Figure 1 Calculated argon lamp emission for a fixed magnetic field of 1700 G referenced to the oxygen absorption line at $13,093.65 \text{ cm}^{-1}$. Also shown is the Ar emission line in the absence of a magnetic field.

1.4 Project Objectives

The overall objective of the project was the development of a sensor which can verify the proper gas filling of insulated glass (IG) windows in a non-intrusive and non-destructive manner. It also addresses the need for a field-based sensor which will determine if window seal damage has occurred. This sensor can be adapted for production quality control (testing for complete substitution of air by argon or other such low thermal conductivity gas), evaluating inventory units, and testing IG window integrity in the field.

Success criteria were set as follows:

- Laboratory demonstration of a sensor that can detect less than 2% oxygen within the air gap of an IG panel with a signal-to-noise ratio of two. This shall be determined using the r.m.s. (root mean square) noise level with one minute integration time. The span (scale factor) accuracy of the measurement (determined using a conventional sampling oxygen sensor) shall be within 25% at 2% oxygen content (that is, an absolute accuracy of 0.5% oxygen).
- Design, construction and testing of a prototype unit meeting the above performance standards.

In addition, an assessment of the OWL-IG technology in terms of extending its use to other markets such as home inspection of installed IG windows was to be made. Initial plans for reducing size, weight, complexity and cost were to be provided.

2. SENSOR IMPLEMENTATION

2.1 Implementation Of Wavelength Modulation

Under sine wave modulation of the magnetic field, the lamp output comprises two frequency (i.e., wavelength)-modulated components with orthogonal circular polarizations (shown in **Figure 2**). One of these is selected by a fixed circular polarizer (a combination of a quarter-wave plate and a linear polarizer), providing one wavelength-modulated light beam with fixed linear polarization. The extent of the wavelength modulation is determined by the strength of the applied magnetic field. If oxygen is present in the subsequent beam path, the beam intensity will also be similarly modulated because of the differential absorption that takes place as the wavelength is scanned. In practice, the magnitude of the AC magnetic field is chosen such that the absorption measurement effectively integrates over a wavelength range which includes the entire oxygen absorption line, not just its peak. Thus, the detection scheme, as implemented, provides a column density measurement (using Beer's Law) and is sensitive to temperature and pressure changes, primarily in response to the ideal gas law.[12] However, this also ensures that its calibration is independent of fill gas composition. This is in contrast to the water vapor sensor, which, because of its square wave modulation between two fixed frequencies, operates as a mixing ratio detector, but with the drawback that its response is sensitive to the exact composition of the gas fill through the pressure broadening coefficients of the constituent gases.[6,7]

2.2 Lamp Development

A key element of the wavelength modulation scheme is the choice of a suitable lamp. The positive column discharge lamp previously employed for water vapor detection suffers from three serious drawbacks.[12] First, its output at 763.7 nm is limited by the fact that this argon emission line is sufficiently strong to become self-absorbed in a finite column length. Second, a positive column discharge lamp is an inherently noisy device - lamp noise becomes the limiting factor instead of lamp intensity. And third, the lamp requires a fairly high external magnetic field (~1500-2000 G) to provide the proper splitting of the emission line and thus would require a bulky and power-consuming electromagnet.

We have instead chosen to use a type of lamp, a surface glow discharge lamp, in which high voltage is applied to the cathode, inducing a plasma in front of the cathode surface.[13] The electrical circuit is completed by electron migration within the argon fill gas to the ring anode region. At proper running conditions, the active volume is restricted to a small region in front of the

Figure 2 Frequency modulation of argon lamp emission by the AC magnetic field. The emission is composed of two circularly polarized components which are 180° out of phase with respect to one another. A circular polarizer is used to isolate one of these components and convert it to a fixed linear polarization which then propagates down the beam path.

cathode surface. We have found this type of lamp provides a comparatively high intensity beam at the wavelength of interest and is sufficiently quiet that we are able to dispense with the noise reduction circuitry employed for the water vapor sensor. Furthermore, through proper choice of the magnetic properties of the electrode material, the required external magnetic field can be greatly reduced. This is accomplished by choosing a cathode made from a magnetic material; when an external magnetic field is applied, the effective magnetic induction in the cathode bulk is the sum of the external field strength and the induced magnetization, a function of the cathode permeability. Because this nominally bulk effect does extend some distance from the cathode, the gas in the discharge region is in an effective magnetic field much greater than it would otherwise be.

A schematic and photograph of the custom-made lamp are shown in **Figures 3 and 4**. It comprises a Kovar cathode, which provides the discharge surface, a nickel ring anode and a glass vacuum housing with a polished window at one end. The choice of Kovar, an iron alloy with approximately 29% nickel and 17% cobalt, was predicated on the fact that it has a sputtering rate that is less than that of soft iron (an otherwise preferred magnetic material) and has the required magnetic properties (relatively high magnetic permeability and Curie temperature and low magnetic losses). [14] The lamp, which is filled with ultrahigh purity argon, also contains a getter to remove any unwanted gas impurities. With a 2.5 mm diameter cathode, a lamp current of 4 mA, and f/1 collection optics, in-band lamp emission intensities approaching several hundred nanowatts were measured.

In order to ascertain the spectral properties of the surface glow lamp under the influence of a magnetic field, the internal state distribution of the argon in the discharge region was probed using optical absorption spectroscopy. We assume that the absorption spectrum of the argon discharge will mirror its output as a lamp. Thus, we can measure not only the exact output wavelength of the lamp as a function of the applied magnetic field using an electromagnet, but its linewidth as well. In these studies, the output of a vertical cavity surface emitting laser (VCSEL) was directed through the lamp window and onto the surface of the cathode which was used as a reflecting surface. The reflected light beam was then directed onto a silicon photodetector. The laser beam was focused so as to cover as large a volume of the discharge region as possible. The absorption of that light by the plasma provides information about the concentration of excited states of argon (which are responsible for the lamp emission).

Figure 3 Schematic of surface glow lamp.

Figure 4 Photograph of argon discharge lamp produced by Hamamatsu Corp.. The black spool in the picture is there for support of the lamp..

VCSEL's are solid state lasers which can be tuned through a narrow region of the electromagnetic spectrum using a combination of temperature and current control.[15] They are notable for: ability to operate at or near room temperature; their linear response to changes in current; and their narrow linewidth (10 MHz or 0.0003 cm^{-1}). The particular laser used in these studies could be tuned over approximately 1.5 nm; the oxygen absorption line and the argon lamp emission line were used to calibrate the wavelength of the laser output.

In a typical experiment, the output of the laser is modulated at 1.0 kHz while it is being current tuned. The resulting current from the silicon photodiode detector is demodulated using a lock-in amplifier; a computer records the resulting signal as a function of the laser tuning current. When the laser current tuning curve is properly calibrated, the exact wavelength position of the absorption feature can be obtained. **Figure 5** provides a summary of the data obtained by interrogating the surface glow lamp in this manner while a DC magnetic field was applied. The frequency shift is approximately linear with respect to applied magnetic field, although there is a hint of saturation at the highest applied magnetic field. Note that at the frequency shift which coincides with oxygen absorption, 0.14 cm^{-1} , an external magnetic field of only $\sim 390\text{ G}$ is required, indicating that the magnetic induction effect is quite significant. The measured line widths of the magnetically shifted argon emission line are up to 20% broader than that of the unperturbed emission line.

Upon the completion of the lamp testing, we were able to have a commercial company build and supply these lamps to us based on our proprietary design. Hamamatsu, Inc. of Japan is perhaps the world's leading supplier of small emission lamps, photomultiplier tubes and photon detectors, and associated detection equipment.

Figure 5 Measured frequency shift of argon lamp emission as a function of applied magnetic field (measured in the absence of the lamp). Shift is shown with respect to that of the zero-field emission at $13,093.79 \text{ cm}^{-1}$. The oxygen absorption line frequency is noted on the figure ($\Delta f = 0.14 \text{ cm}^{-1}$).

2.3 Magnetic Circuit Design

The initial surface glow lamp was built with an as-produced nickel feedthrough as the cathode. This was found to have too low a permeability and/or saturation flux density to be used with a solenoid of acceptable power consumption. To better understand this problem, we used the Maxwell finite-element magnetostatic design package (Ansoft, Pittsburgh, PA) to calculate the expected field strength. Qualitatively, the results followed our observations, but the calculations (using a published B-H curve for annealed Ni [16]) showed an even higher requirement for solenoid current than actually seen. This difference probably was the result of different magnetic properties of the nickel feedthrough (e.g. composition, heat treatment, and subsequent work-hardening) compared to the sample used for the above cited data.

We next designed a cap for the cathode, made of Hiperc 50A alloy (Carpenter Specialty Alloys, Wyomissing, PA). This high-cobalt-content iron alloy offers the benefits of high saturation flux density in the 2 T (20 kilogauss) range, and well characterized magnetic properties. **Figure 6** shows the mechanical arrangement of the magnetic circuit (only components with relative permeability > 1 are shown; the grid is 0.05" per minor division).

In the figure, note the step at the upper end of the cathode cap. This fits into a hole in a ceramic spacer used to keep the cathode centered mechanically, which thus defines the 0.1" active cathode diameter. Behind the spacer, the cap and the Ni feedthrough are covered with ceramic "fish spine" beads, to prevent plasma current from flowing to other than the active area of the cathode.

Figure 7 shows a contour plot of $|B|$ for the complete lamp, while **Figure 8** is a detailed view around the cathode cap. The model results are in excellent agreement with experiment, e.g. at 1350 Ampere-turns, corresponding to 3 A through the 450 turn winding, the field at the surface is found to be 0.225 T, slightly over the value that shifts the argon line into coincidence with the oxygen absorption line. This is what is in fact found spectroscopically.

In the final production lamp, the Hiperc cathode was replaced with a Kovar cathode. As noted in the previous section, Kovar proved to have sufficiently good mechanical and magnetic properties to produce lamp behavior similar to that of the Hiperc.

Figure 6 Mechanical arrangement of the magnetic circuit. Only components with relative permeability greater than 1 are shown.

Figure 7 Contour plot of $|B|$ for the entire lamp.

Figure 8 Detailed view of $|B|$ in the region of the cathode cap.

The solenoid is wound on a 300-series stainless steel (nonmagnetic) tube, with soft iron end plates and shell. The diameter of this tube must be large enough to clear the window of the lamp, and this leaves a gap over the metal tube that supports the window. In this gap, a split aluminum tube serves as both a spacer and as a means of cooling the inside of the solenoid. Heat sinks are attached to the inner end of the two halves of this split tube.

In normal operation, the temperature rise of the solenoid is $\sim 50^\circ\text{C}$ as measured on the surface of the shell. This temperature increase has a substantial effect on the resistance of the winding: the temperature coefficient of resistivity of copper wire [14] is $6.8 \times 10^{-3} / ^\circ\text{C}$, and thus even if the temperature rise were uniform throughout the winding, the change in resistance would be 40%, with a corresponding decrease in the current when the solenoid is driven from a constant voltage. In warming up from room temperature, 22°C , the actual increase in solenoid drive voltage needed to maintain constant current is a factor of 1.75, corresponding to an average temperature rise in the winding of 82°C . In order to overcome this problem, the solenoid current is stabilized against variations in the resistance of the winding caused by temperature changes.

The drive frequency of the magnet is 256 Hz. This is derived from a digital divider chain that starts with a 32,768 Hz crystal controlled oscillator. The output of this digital divider is a square wave, but it is not practical to excite the solenoid with a square wave current; doing so would result in a large voltage spike at each change of the current's polarity, due to the 6.5 mH inductance of the solenoid. Instead, the arrangement shown in **Figure 9** is used. The digital signal first excites a tuned circuit ($Q \sim 100$) to transform the digital square wave into a sine wave of several volts amplitude. This is then amplified by a conventional audio amplifier rated at up to 100 Watts/channel. The amplifier output should drive a resistive load of nominally 8 ohms. The amplifier readily handles the resistance of the solenoid ($2\ \Omega$ cold, $3.5\ \Omega$ at operating temperature), but the reactance of the solenoid by itself, $\sim 10\ \Omega$, would limit the current that could be delivered. Therefore, the $60\ \mu\text{F}$ tuning capacitor is added in series with the solenoid. This provides capacitive reactance to cancel the inductive reactance of the solenoid.

Also shown in the figure is a 20 turn coil designated "B-dot". This is wound onto the surface of the tubing immediately behind the window, where it has a reduced wall thickness to facilitate sealing to the glass. This reduced diameter allows room for the coil (made of AWG 40 wire) to be wound onto the tube and insulated with Kapton tape. The thickness of the coil is small enough that it does not touch the split aluminum heat sink tubes noted above. The voltage appearing at the terminals of this coil is proportional to the time derivative of the flux linkage, hence the designation B-dot.

SOLENOID DRIVE CIRCUIT

TYPICAL VALUES:

V_a	4 V
V_s	18 V
I	2 A

Temperature Rise 30 -- 50 C

Figure 9 Solenoid Drive Circuitry

In the signal processing software, described below, this signal is demodulated by in-phase and quadrature reference signals at 256 Hz. The vector sum of the demodulated signals has both amplitude and phase information about $B\cdot$, and thus about the magnetic field B . The magnitude is compared to a target value, supplied to the program in a setup parameters file, and the error signal corrects the numerical value that is sent to a digital-to-analog converter (DAC). The output voltage of this DAC is switched at 256 Hz to provide the signal that is sent to the audio amplifier. In that way, the solenoid current is stabilized against variations in the resistance of the winding caused by temperature changes.

The phase signal that results from demodulating $B\cdot$ is used as the phase reference for the demodulation of the optical signals. The phase offset of these signals from $B\cdot$ are also supplied in the setup parameters file; this is a far more flexible and convenient way to adjust the phasing of the demodulation than an analog trimpot-adjusted phase shifter would be.

2. 4 Measurement Of Oxygen In Argon-Filled Insulated Glass Windows

Figure 10 shows a schematic of the apparatus used to measure the oxygen concentration within a double-paned insulated glass window. A beam of light from the lamp, formed by a collecting lens, deflects off a concave mirror, goes through the window onto a first surface plano mirror, back through the window, through a focusing lens and onto a silicon detector. The focal lengths of the collecting and focusing lenses and concave mirror are chosen to minimize beam size and to maximize light collection at the detector. An inexpensive organic circular polarizer film was used to select one frequency component emitted by the lamp. An interference filter, which is attached to the detector, serves to limit the light which reaches the detector to a narrow (10 nm wide) band centered around the frequency of the oxygen absorption line. The choice of an oblique angle for the angle of beam entry into the window and the use of a double pass through the window was made in order to increase the path length within the window cavity as much as possible. Modern residential insulated glass windows have fill cavity depths that are typically 10 mm or less; this arrangement provides an almost four-fold increase in path length over a single pass head-on arrangement. The angle of incidence was also chosen to be Brewster's angle in order to minimize any unwanted reflections from the various glass pane surfaces. The circular polarizer axis thus has to be aligned to the vertical orientation with respect to the schematic.

Figure 10 Schematic of setup for the measurement of oxygen within a double-paned insulated glass window.

As can be seen from the schematic in Figure 10, any oxygen absorption measurement includes the air path outside the window as well as inside. In fact, the air path outside the window is a factor of five greater than the path to be measured. Thus, a difference measurement must be made; all measurements are made first with the window absent and then with the window in place. This protocol not only subtracts the ambient air path, but also subtracts any baseline drift in the instrument. One consequence of this design is that the reflecting mirror behind the window must be moved to accommodate the absence or presence of the window. Because the glass panes have an index of refraction which is not the same as air, the presence of the window deflects the light beam sufficiently to require an adjustment.

The window used for this experiment was a commercially available window with a low-emissivity coating, a total window thickness of 15 mm and glass pane thickness of 2.5 mm (i.e., a gap of 10 mm).[17] In order to avoid window failure, the window was flushed with the appropriate gas fill at ambient pressure. This was accomplished by inserting tubes through the metallic channels which keep the panes separated and provide structural rigidity. The amount of oxygen in any given fill was measured using a Mocon oxygen analyzer which claims to be accurate to within 0.1% oxygen. The data are presented in **Figure 11**. Sensor signal is plotted versus oxygen concentration (as a component in air). Also shown on the top axis is the amount of argon within the window. (Note that the oxygen is 21% of air by volume). A linear least squares fit to the data is shown which indicates that the calibration is indeed linear, as expected. One consequence of this finding is that a two point calibration - one in pure argon and one in pure air - is sufficient to provide reasonable accuracy. Another is that the calibration is independent of gas composition. And if pressure and temperature are measured simultaneously, a one-time calibration can also be applied under a wide range of operating conditions.

Sensor precision was measured by flushing the test window with five different gas fills which ranged from 100% argon to ~50%Air/50%Ar and then executing twenty complete window-in/ window-out cycles for each gas fill. The total measurement time for each cycle was 32 seconds (16 seconds for each part of the cycle). The results are shown in **Figure 12** for a variety of oxygen (as air) concentrations in argon. Averaged over the complete set of 100 cycles, the r.m.s. noise of the measurements was 0.18% O₂ (an air equivalent of 0.86%), well within any requirements of the glass window manufacturing industry.

Figure 11 Sensor response as a function of the fraction of oxygen (as air) mixed with argon within the window cavity. Also shown is a linear least squares fit to the data

Figure 12 Reproducibility of sensor readings as a function of oxygen (as air)/argon fill ratio. Each measurement is the difference between readings with the window in place and with it removed. The precision averaged over all the measurements was 0.18% oxygen.

In summary, we have designed, built and tested a non-contact sensor (known as the OWL-IG) capable of verifying the presence or absence of oxygen (air) within a double-paned insulated glass window. It relies on an optical absorption measurement which utilizes an absorption line in the oxygen atmospheric A-band centered at 760 nm. It is capable of determining the concentration of air within the window with a precision of $\pm 1\%$ with an integration time of 16 seconds.

3. IG WINDOW SEAL INTEGRITY MONITOR

3.1 Overall Monitor Design

The OWL-IG window seal integrity monitor is designed to operate as an autonomous operating unit with minimal user input. Two photographs are presented in Figures 13 and 14 which show an insulated glass window inserted into the measurement volume of the monitor. The monitor measures approximately 15 x 22 x 50 cm (W x H x L) in size and weighs approximately 8 kg. The sheet metal housing encompasses the optical path shown in Figure 10 including the lamp/solenoid assembly, beam focusing optics, steering mirror and detector. Also housed within are all the necessary electronics including power supplies and a PC-104 format computer. As discussed later, sensors which record the temperature, pressure and relative humidity are also included.

From the schematic shown in Figure 10 above, it can be seen that the amount of oxygen within the window volume is a small perturbation of the total amount of oxygen within the optical path of the beam (which is air). In order to accurately measure the amount of oxygen within the window, the effect of the air path outside of the window must be eliminated. The first approach to this issue is to purge this path with some inert gas such as nitrogen or argon. This approach would have required the use of a sealed box that would allow for purging. However, aside from the practical issues of cost and ease of use, this would have been exceptionally difficult to accomplish. The air path outside the window is approximately five (5) times greater than inside the window. In order to accurately measure 0.5% oxygen, the box would have had to been purged to 99.9% inert gas or better, a rather difficult task. Thus, this approach was rejected.

The second approach is to take measurements with and without the window present and observe whether there is a difference. However, a closer inspection of the geometries involved indicates that this approach is not that straightforward. Figure 15 shows the exact geometry involved. One notices that the window glass pane deflects the beam such that the steering mirror behind the window must be moved some distance back so that the beam can be properly steered into the detector. (An alternative is to keep the mirror fixed and move the detector, a more difficult task!) Further calculation of this effect indicates that the effective beam paths in both cases are not the same; the mirror displacement is less than that of the window pane thickness. Thus, a simple subtraction cannot be made. However, the exact window dimensions (overall window thickness and glass pane width) must be known for a determination of oxygen content to be made. These issues will be addressed in the next subsection.

In order to accommodate this subtraction, a platform using plastic rollers was constructed to fit around the sensor. As shown in Figures 13 and 14, the window can simply be placed on the platform and rolled into the measurement volume. Sensors located within the monitor alert the computer to the fact that the window is present, triggering a measurement of the absorption signal. When the window is rolled out, another sensor triggers the background measurement. Once this is performed, the calculated oxygen concentration is read out on a display located at the top front of the monitor. The keypad under the monitor allows the user to enter the total window thickness, which must be measured by the user.

Figure 13 Photo of OWL-IG

Figure 14 Photo of OWL-IG

Figure 15 Displacement of optical beam through IG window. Also shown is the required displacement of the steering mirror in order to compensate for this effect.

3.2 Automated Window Thickness Compensation

As noted before, the distance the mirror moves is related to the thickness of the window panes. Figure 16 shows the geometry of the beam path through the window. Snell's Law indicates that the beam path is dependent on the index of refraction of the glass. Thus, in the limit that the angle of incidence of the beam is Brewster's angle, which is what is used on this monitor, the mirror movement distance, d , is related to the window pane thickness, w , by the following:

$$d = [1 - 1/n^2] \cdot w$$

where n is the index of refraction of the glass. For most glass used in IG windows, n is approximately 1.515 and

$$d \approx .56 w$$

further simplifying the expression given above.

In the original design of the monitor, our intention was to have the user enter both the total window thickness, W , and pane thickness, w and then calculate the required mirror movement. Given that the accuracy of the window pane thickness is probably the limiting factor in the accuracy of the measurement, we decided to measure it directly using the optical beam. We discovered that we could do this by simply moving the mirror up and down until the beam intensity was maximized, indicating that the mirror was now at its 'correct' position. By using a computer control of this measurement, we are able to determine d within 0.05 mm and then calculate w . Thus, the only user input is the value of the total window thickness.

The movable mirror was attached to the end of a short section of centerless-ground stainless steel rod of 0.75" diameter. This moved in a Delrin bushing that had been reamed to a precision slide fit in the rod. A slot in the wall of the bushing provided access for a pin of 0.125" diameter that was threaded into the side of the rod. This pin was moved by a cam, which consisted of a radial slot in a disk, which was rotated by a servo. Over the limited range of angles used here, $\sim 30^\circ$, this arrangement gave acceptable linearity in the conversion of rotary to linear motion, after correction by a software lookup table. The servo was a standard unit designed for use in model aircraft; to insure freedom from tilting of the cam disk, caused by the unbalanced force on the cam by the drive pin, a servo with ball bearings on its output shaft was used. This type of servo is controlled by a train of variable width pulses. These were generated by a programmable counter that was part of the signal processing electronics.

Figure 16

Geometry of beam path through window pane. Note that the beam is effectively displaced by an amount $[z-x]$ compared to the absence of the window pane which is less than the pane thickness. If the angle of incidence is at Brewster's angle, this amount is readily calculated knowing the index of refraction of the window glass.

3.3 Sensor Calibration and Precision

We use the following nomenclature (and relating it to Figure 15) :

w = pane thickness (t_w)
W = total window thickness equal to window gap (t_g) + 2 • w
d = mirror movement distance
L = total air path in absence of the IG window unit
H = humidity (partial pressure)
T = temperature
C = calibration constant (corrected to standard temperature and pressure, T_0 and P_0 1 atmosphere and 298 K respectively).
X = concentration of oxygen within the IG window

The signal, S , measured by the monitor in the absence of the window is, according to Beer's Law:

$$S = C \cdot ([P-H]/P_0) \cdot (T_0/T) \cdot L \cdot 0.21$$

where 0.21 is simply the mole fraction of oxygen in the air; the pressure has been corrected for the amount of water vapor in the air as well.

When the window is placed in the optical path and the mirror moved such that the beam reaches the detector, the signal, S' , is:

$$S' = C \cdot 0.21 \cdot ([P-H]/P_0) \cdot (T_0/T) \cdot (L-W+2d) + C \cdot X \cdot (P/P_0) \cdot (T_0/T) \cdot (W-2w)$$

where the first term is the amount of oxygen in the optical path outside the window and the second term is a contribution from the optical path within the window. Note that the pathlength in the first term has been diminished by an amount equal to the thickness of the window and then increased by the movement of the mirror. The pathlength in the second term is just the gap thickness. Note that there is no correction for humidity in the second term; it is assumed that its concentration is equal to zero because of the effect of the desiccants within the window gap. We also assume that the pressure and temperature within the window are the same as the ambient conditions.

If one measures the signal without and with the window in place, the difference in the signal levels is just:

$$S-S' = C \cdot ([P-H]/P_0) \cdot (T_0/T) \cdot 0.21 \cdot (W-2d) - C \cdot X \cdot (P/P_0) \cdot (T_0/T) \cdot (W-2w).$$

Thus, with knowledge of P, T, W, w and d and a monitor calibration, one can readily determine X . The fact that this solution is linear in X also indicates that the monitor can be readily calibrated by measuring the signal difference as a function of X with a fixed window. If the data is plotted as signal difference versus oxygen concentration, either the slope and or intercept of the least squares fit to the data will provide the calibration constant.

In order to calibrate the window sensor, multiple measurements were made using a standard IG window which could be filled with flowing oxygen, air and argon corresponding to 100%, 21% and 0% oxygen fills respectively. The window was put in and taken out of the unit for each measurement. As a result, the measurements are independent of one another. The results of this test are shown in Figure 17. Note that as before, the plot of sensor readings versus produced a straight line as a function of oxygen concentration. Also note that the sign of the sensor reading changed! This is caused by the fact that in the presence of an argon fill in the window, there is less absorption with the window in place than with it absent. But when the window is filled with 100% oxygen, more absorption takes place compared to no window and the resulting difference in absorption signals, $S-S'$, is now negative.

This measurement procedure also provides a good test of sensor precision. The calibration constant determination requires not only the measurement of sensor response, but also atmospheric pressure, humidity and temperature. It also requires the determination of the window pane thickness from the steering mirror movement distance. From statistical principals, the overall precision is the square root of the sums of the squares of the precisions of each individual component. Using manufacturer's specifications, the precision of the temperature, pressure and humidity measurements are all better than $\pm 0.1\%$! From the data in Section 2, we know that the basic precision of the oxygen measurement is $\sim 0.25\%$ in a 16 second measurement period. However, the measured precision of the total sensor system was $\pm 0.50\%$ oxygen as can be seen from the data in the top part of Figure 17. This would indicate that the movement of the steering mirror and determination of the pane thickness introduces a precision error which is larger than any of the other components. (It is also possible that some unknown factor contributes to the overall precision.) Thus, using a longer measurement period would not improve the instrument precision. Further improvements in the mirror movement mechanism and algorithm that determines the proper mirror position would presumably reduce the sensor precision limits.

Sensor accuracy has not yet been suitably addressed. The sensor can be very accurately calibrated for a given set of conditions. The calibration performed here is good to within $\pm 0.2\%$ oxygen; however it is valid only for the window used and the temperature, pressure, and humidity

Figure 17 Sensor Response as a function of oxygen mole fraction. The upper section of the figure shows the residual of the points with respect to a linear least squares fit of the data shown in the lower section. The combination of the precision and accuracy of the device is just the average residual or 0.50% O₂.

under which it was performed. No attempt was made to use IG windows with other dimensions. This step is required in order to determine the sensor accuracy. We also note that the calibration is only as accurate as the physical measurement of the window thickness. Typical measurements of this parameter have errors on the order of $\pm 0.3\%$. This error is caused, not only by the ability to read a measurement device, but by the fact that the window unit is not of completely uniform thickness. This error contributes to a direct offset in the reading. And a more fundamental limitation is that the monitor assumes that the window gap is at the same temperature and pressure of the surrounding ambient atmosphere. If the monitor is used while the window is being filled or directly afterward, this is a good assumption. However, if the window being checked was filled under far different conditions, a several per cent offset in the reading could easily be introduced.

3.4 Comparison of Monitor to Competing Technologies

The competing technology for the OWL-IG is the GasGlass™, produced by Sparklike, Ltd. of Helsinki Finland. Its technology is based on spark-induced emission within the window fill gas. As such, it requires that the spark-inducing sensor be placed directly on the window. The emission is collected by an optical fiber which transmits the radiation back to a miniaturized spectrometer which determines the wavelength distribution and intensity of the light. A proprietary algorithm is used to determine the amount of argon within the window gap. This sensor is not calibrated for any gas besides argon and cannot accurately measure argon concentrations below 80%. A comparison of this technology with that developed here is presented in Figure 18.

The positive aspect of the GasGlass is that it provides high precision measurements of windows which either have not or are only on the verge of failing. It is also quite easy to use. On the other hand, its accuracy on any given window is suspect; it is calibrated for one particular set of window dimensions and no systematic correction can be applied for other windows. The U.S. supplier, FDR Technologies of Buffalo, MN is working on providing calibration standards for general use. It also is not usable with any fill gas besides argon.

It is important to note that the need for the GasGlass to produce a spark within the window gas makes it unsuitable for a number of new window technologies. First, the GasGlass cannot be used with any window that uses a plastic barrier of any kind. At best, the interpretation of the signal would be difficult and at worst, the barrier integrity would be compromised. For any kind of electrochromic window, which essentially utilizes semiconductor coatings, the GasGlass could cause complete window failure. The technology presented in this report is completely compatible with all window technologies as long as the various coatings and/or plastic barriers did not absorb light at the 763 nm wavelength used by this monitor.

COMPARISON TO GASGLASS

Complementary Technologies

<u>Aerodyne</u>	<u>GasGlass</u>
<ul style="list-style-type: none">• Detects Oxygen (0-100%)• Non-Contact, Non-Destructive• Applicable to All Gas Fills• Inherent Accuracy• Readily Recalibrated• Precision: $\pm 2\%$ Air	<ul style="list-style-type: none">• Detects Argon (above 80%)• Spark Discharge, Possible Coating Damage• Argon Fill Only (In principle, others as well)• Subject to Window Specifications• Factory Recalibration• $\pm 0.5\%$ (90-100%) $\pm 1.0\%$ (80-90%)

Figure 18 Comparison of Aerodyne and GasGlass monitors.

3.5 Recommendations For Future Development Of The OWL-IG

The effort described above represents an attempt to produce a benchtop instrument for use in an IG factory setting. A much larger market, with far larger impact on energy usage, is the inspection of IG windows installed in private homes. (Sales of IG windows to private homes represents over 80% of the total American IG window market.) We note that there are 10,000 home inspectors in the U.S. alone, of which 6,000 belong to the American Society of Home Inspectors, who are potential users of this technology. There is also be a substantial foreign market for this technology; both Canada and European housing codes mandate the use of IG windows in new construction. The impetus behind this effort was a study presented at the SIGMA 2000 meeting that indicated that fully half of all new IG windows being produced might not meet their specified argon fill levels! This circumstance leads to energy losses which total 0.035 quads annually. This set of circumstances has also created a serious consumer liability issue.

More importantly, the issue of seal failure in the installed base of IG windows and the concomitant loss of energy savings is a matter which is not being addressed at all. A common complaint among consumers is the presence of 'fogging' in windows, a condition which is caused by the diffusion of water vapor into the window gap due to seal failure. Significant argon out-diffusion and air in-diffusion has occurred by this point, although there is no way to currently measure this process. The sensor would allow both window manufacturers and homeowners to determine if seal failure has occurred before visual signs are present. It would work by determining the presence or absence of air between the panes of the IG window unit.

The critical technical obstacle in developing a sensor suitable for inspecting installed IG windows in private homes is the need to decrease the size, complexity and cost of the sensor. The current instrument, designed to meet the demanding specifications of the window manufacturing industry is approximately 0.06 m³ (2 ft³) in size and weighs approximately 8 kg (20 lbs.). A unit for home inspection use should be substantially smaller in weight and size. An artists' rendition of the a possible sensor is shown in **Figure 19**. Note that the sensor consists of two units - one housing all the electronics, lamp/magnet assembly and readout and the other the measurement pod. They are hooked together using a tether which contains an optical fiber bundle and wires.

Figure 19 Artist's rendition of IG window seal integrity sensor

Currently, the OWL-IG exhibits a precision and accuracy of 2.5% air (2σ). For the home inspection market, a reasonable goal is a sensitivity of 25% air (2σ) within an integration time of 15 seconds. This corresponds to an argon gas fill level of 75%, a level which would indicate that the window has definitely failed. This reduction in precision and accuracy requirements would allow for the development of a suitable sensor.

In order to meet the requirements discussed above, the following suggestions for future development are presented:

- Miniaturization of the actual measurement probe while allowing for the development of a two component system - one which will house the electronics, lamp/magnet assembly, and computer, and the other which will comprise the measurement probe itself. A schematic of the suggested optical path is shown in **Figure 20**.
- Re-engineering of the surface glow argon discharge lamp to produce a design which is at least 50% smaller. The successful development of such a lamp would permit the use of a much smaller, lower power consumption and commercially available solenoid to provide the magnetic field.
- Redesign of the electronics in order to substantially reduce cost of the components. All components dealing with the digital processing of the data should be replaced with a single FPGA (Field Programmable Gate Array) chip. In addition, a lower level microprocessor should replace a DOS-based computer (PC104-386 PC) which is currently used.
- Inclusion of a window thickness monitor to allow for measurement automation. In the current factory-based version, the total window thickness, a key measurement specification, must be measured by the user; its value is then entered through a keypad. A less accurate, automated window thickness measurement would allow for complete automation of the measurement process.

Figure 20 Sketch of optical layout of IG window home inspection monitor.

4. CONCLUSIONS

A sensor system (the OWL-IG) capable of determining the presence of unwanted oxygen (air) within the gap of a double pane insulated glass window has been designed, constructed and tested. The sensor system is non-contact and non-invasive. It operates by using the optical absorption of oxygen in the atmospheric A-band centered at 762 nm. Light emitted by an argon-filled surface glow discharge lamp is Zeeman-tuned on and off an oxygen absorption line using an AC-modulated electromagnet. In the presence of oxygen, the change in the measured intensity of the lamp, obtained using standard demodulation techniques, is proportional to the oxygen column density. The sensor operates by measuring the amount of oxygen within its optical beam path with and without the presence of the IG window. The difference, after correction for pressure, temperature, humidity and the dimensions of the window, provides the oxygen concentration within the window cavity. The performance of the system is that it can detect oxygen with a precision of $\pm 0.5\%$ using a 16 second integration period.

The OWL-IG sensor is suitable for deployment in a manufacturing environment and could easily be refined for applications in home and/or commercial building inspections. It is light-tight, insensitive to mechanical and electrical interference and automatically compensates for changes in ambient temperature, pressure and humidity. It is also designed to minimize the effects of dust and dirt in the environment on its performance. It can be calibrated in the field using a simple two-point calibration procedure (air and pure argon). Approximately two windows a minute could be tested at the stated precision. It could also be readily adapted for assembly line testing at a much higher sampling rate with limited loss of precision.

This sensor offers several advantages over the current technology, the GasGlass™ sensor from Spark-Like Ltd.. The GasGlass uses a spark-induced breakdown to produce emission which is then analyzed to provide the amount of argon in the window gap. The GasGlass must be placed directly on the window and is capable of producing small holes in the window coatings. It also is sensitive to argon only, and at concentrations above 80%; thus, it has difficulty reliably measuring the amount of argon in a failing window. Another drawback is that cannot measure any other gases such as oxygen, nitrogen, krypton, etc.. It is also only calibrated for a specific window used by Spark-Like and is difficult to calibrate on site. While this sensor has found some acceptance within the IG window community, there are considerable concerns about its performance limitations and its potential for damaging the window. Its selling price is also considered somewhat high.

The OWL-IG overcomes many of the problems associated with the GasGlass. It is non-contact and non-intrusive and reliably measures any oxygen concentration from 0-100%. It is not affected by the chemical makeup of the gas fill. It can be readily recalibrated at the factory or in the field, although its calibration, as supplied, should be sufficient. It will also not damage any sensitive coatings that have been applied to the window. This is especially important for the new generations of window technology which will undoubtedly introduce new and sophisticated innovations such as semiconductor coatings and electrochromic controls. The OWL-IG has proven to be accurate, reliable, versatile and completely nondestructive and compatible with future advances in IG window technology.

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LIST of ACRONYMS

A	ampere
AC	alternating current
Ar	argon
AWG	American wire gauge
B	magnetic induction
cm	centimeters
cm ⁻¹	wavenumbers
DAC	digital to analog converter
DC	direct current
EEPROM	erasable programmable memory
FPGA	field programmable gate array
G	gauss
H	magnetic field strength
Hz	Hertz (unit of frequency)
IG	insulated glass
IGMAC	Insulated Glass Manufacturers Alliance of Canada
IO	input/output
LCD	liquid crystal display
mm	millimeters
NETL	National Energy Technology Laboratory
Ni	nickel
Ω	ohm
O ₂	oxygen
OS	operating system
p	pressure
PC	personal computer
r.m.s.	root mean square
SIBES	spark induced breakdown spectroscopy
SIGMA	Society of Insulated Glass Manufacturers
T	Tesla
T	temperature
VCSEL	vertical cavity surface emitting laser