"A Compact Wearable Personal Monitor for Real-Time Detection of NO_2 in Mines"

Closeout FOA PAR09-139

December 31, 2016

Issued by
Centers for Disease Control and Prevention (PGO)
Office of Grant Services
4676 Columbia Parkway
Cincinnati, OH 45226-1922

Federal Grant: FOA PAR09-139 Award R21 0H 010116

Contractor:	Platypus Technologies, LLC
Business Address:	5520 Nobel Drive, Suite 100 Madison, WI 53711
Phone:	608-237-1274

Title of Work:	A Compact Wearable Personal Monitor for Real-Time Detection of NO_2 in Mines
Contract Expiration Date:	8/31/2015
Reporting Period:	09/01/2012 - 8/31/2015

Comprehensive Final Report: Development of a Compact Wearable Personal Monitor for Real-Time Detection of NO_2 in Mines

Abstract:

In this report, we summarize the work aimed at developing a prototype for a compact, person-wearable monitor for real-time detection of NO_2. The prototype monitor developed by Platypus Technologies consists of a sensing element that exhibits an optical response when exposed to gas streams containing NO_2, and an electronic system that reads the state of the sensing element and produces a visual alarm if NO_2 is detected. The sensing element can detect the presence of NO_2 at concentrations between 0.5 – 10 ppm in less than 1 minute. Moreover, we demonstrate that the LC sensor does not exhibit false-positive responses in the presence of non-target gases, and remains sensitive to NO_2 even in the presence of non-target gases, or under a wide range of relative humidity levels (0 – 80% RH) and temperatures (0 – 35°C). In addition, we built an electronic monitor to accommodate individual LC-based sensing elements, read the state of the sensing elements and alarm if NO_2 has been detected. This prototype personal monitor was successfully tested in a laboratory and in a simulated lab environment, where its wearability and fast detection of NO_2 were tested. Despite the tremendous technological developments achieved under this contract, further work is required to refine the current prototype and bring this technology to market. This work was sponsored by the Centers for Disease Control and Prevention (CDC) under the Contract No. 211-2013-56917, Modification No. 00001.

Introduction:

Nitrogen dioxide (NO_2) poses significant health risks to persons exposed to this gas because of its toxicity to eyes and respiratory membranes. According to the Occupational Safety and Health Administration (OSHA), symptoms of acute overexposure to NO_2 include irritation to eyes, nose and throat; chronic overexposure to NO_2 might lead to chronic bronchitis, breathing difficulty, chest pains, and pulmonary edema. OSHA stipulates the permissible exposure limit to NO_2 at 5 ppm, while the National Institute of Occupational Safety and Health (NIOSH) recommends a exposure limit of 1 ppm NO_2.

NO_2 is emitted into the atmosphere by incomplete fuel combustions in diesel engines. Thus, workers in close proximity to diesel machinery, as in mining operations, incur significant risks of overexposure to NO_2. In these situations, monitors are required to alert workers of the risk of NO_2 exposure. Current monitors for NO_2 are not widely deployed, however, because their elevated cost and constant need for recalibration and maintenance. Because of these constraints in current monitors, individual miners rarely carry personal monitoring devices that alerts them of the risk of exposure to NO_2.

Platypus Technologies aims provide reliable personal monitors to every worker that needs to be alerted of the potential for overexposure to toxic gases. Aligned with this mission, and with generous funding from the CDC, Platypus Technologies initiated efforts to develop and commercialize a fast and accurate personal monitor for NO_2 that is inexpensive and does not require calibration or maintenance. The results of these development efforts are presented in this report, which describes the successful development of an inexpensive person-wearable monitor for NO_2 based on innovative liquid crystal technology by Platypus Technologies.

This report is structured as follows: 1) an overview of chemical sensing using liquid crystals (LCs) will be presented; 2) we present and discuss the experimental data describing the performance of the LC-based sensor for NO_2 under various conditions including varying concentration of NO_2, in the presence of non-target gases, under various temperature and humidity levels, and after storage for 1 month; 3) we present an overview of the electronic monitor used to read and the report the state of the LC-based sensor; 4) we discuss the results from testing of the NO_2 monitors in a lab and simulated mine environments; 5) finally, we discuss further work required to improve the current prototype and bring this sensor technology to market. In addition, in Appendix A of this report, we present the feedback received from staff at the CDC regarding human factors considerations for the NO_2 monitor developed by Platypus Technologies.

Results:

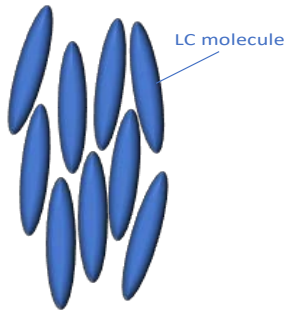

***Figure 2**. Molecules of LC align in the same direction.*

1). Overview of chemical sensing using liquid crystals. Liquid crystals (LCs) are materials that exhibit properties intermediate between those of crystalline solids and isotropic liquids. LCs flow and adopt the shape of their container, like isotropic liquids, but their optical and electric properties depend on the orientation of the sample, similar to crystalline solids. **Error! Reference source not found.** shows an schematic of LC molecules, which are shaped in the form of elongated cylinders and tend to align in the same orientation. This orientational order gives rise to the observed anisotropic properties of LCs. This effect is illustrated in Figure 1, which shows two schematics at the top of the figure representing the molecules of a LC film oriented perpendicular (left) or parallel (right) to the plane of a supporting substrate. When the LC molecules are oriented perpendicular to the surface, the film appears dark when observed with cross-polarized light. In contrast, a film of LC appears bright when viewed with cross-polarized light. The preferred orientation of the LC molecules is determined by the chemical identity of the supporting substrate. Thus, the ability of LC materials to exhibit distinct optical signatures in response to surface conditions underlies the principle of chemical detection developed by Platypus Technologies.

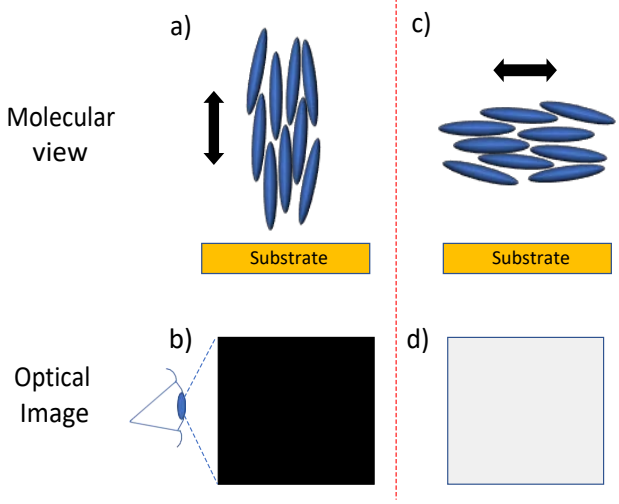

***Figure 1**. (a) Schematic of LC molecules aligned perpendicular to the substrate. (b) Image of LC film containing perpendicularly aligned LC molecules appears dark. (c) Schematic of LC molecules aligned parallel to the substrate. (d) Image of LC film containing parallel-aligned LC molecules appears bright.*

Platypus Technologies designs chemical sensors using two main components: (1) a functional surface chemistry that selectively binds a target molecule, and (2) a LC material that translates the surface binding events into quantifiable optical signals. This design paradigm takes advantage of the ability of LC materials to amplify and propagate surface events into the bulk of the LC. Depending on the properties of the

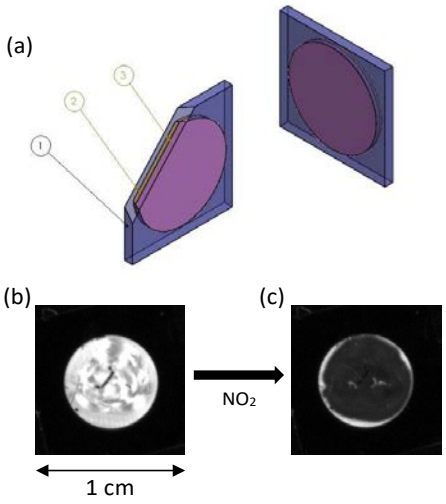

***Figure 3**. (a) Schematic of LC-based sensor element consisting of (1) a glass chip supporting a (2) chemically reactive surface, and (3) a film of LC. (b) Image of a LC-based sensor element viewed with cross-polarized light. (c) Image of LC-based sensor element after exposure NO_2.*

binding chemistry at the surface, the LC molecules align parallel, tilted or perpendicular, and these orientations can be readily visualized when the LC is viewed through crossed polarizers, as detailed in Figure 1. The binding of target molecules to the surface chemistry changes the orientation of the LC and produces a change in the optical properties of the LC film. Using appropriate electronic components, this optical response can be translated into visual and auditory alarms that alert the user of the presence of a noxious compound.

To design a sensor that is selective for a targeted gas, we identified the surface chemistry through iterative experimental design. Guided by physical and chemical principles, we developed and optimized surface binding chemistries that enable the LC to respond to the presence of the target gas only.

In **Error! Reference source not found.**a, we present a schematic of the LC-based sensor element for NO_2 detection developed by Platypus Technologies. The sensor element consists of a 1x1 cm^2 glass plate supporting a chemically reactive surface and a thin film of LC. The identity and methods of preparation of the surface chemistry is proprietary information and thus is not discussed in this report. A picture of the LC-based sensor element viewed with cross-polarized light is presented in **Error! Reference source not found.**b. This film appears bright because the LC molecules are aligned parallel to the supporting surface. The LC loses brightness, however, upon exposure to air streams containing NO_2. An image of the LC-based sensor that was exposed to NO_2 is presented in **Error! Reference source not found.**c, showing that the LC appears dark when viewed through cross-polarized light. As demonstrated by these images, Platypus Technologies developed a sensor element that undergoes a change in optical appearance in the presence of NO_2. The sensitivity and rate of response of the sensor are discussed next.

2). Characterization of sensor response to NO_2: Having developed a method for producing sensors for NO_2, we then exposed these LC sensors to various concentrations of NO_2. Arrays containing four LC films per array were exposed to 1, 2, 3, 5, or 7 ppm of NO_2 in an air stream flowing at 200 sccm. The experiments were carried at room temperature with 0% relative humidity. Initially, the LC sensor films appear bright, as discussed in **Error! Reference source not found.**b. After exposure to NO_2 the brightness of the LC sensors decreased rapidly, although the rate of change in the brightness of the sensors depends on the concentration of NO_2 in the air stream.

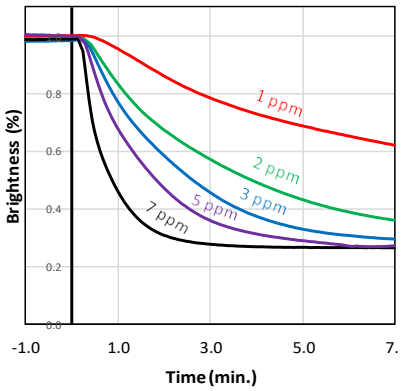

***Figure 4**. Time-dependent response of LC sensors to air streams containing NO_2 at concentrations of 1 ppm (red), 2 ppm (green), 3 ppm (blue), 5 ppm (purple) and 7 ppm (black). Traces represent average response of 4 different LC sensors exposed to NO_2.*

The averaged time-dependent change in brightness of the LC sensors upon exposure to various concentrations of NO_2 is presented in Figure 4, which shows the plot of brightness of the LC sensors as a function of exposure time to NO_2. The plot shows 5 different traces, which correspond to the time-dependent averaged brightness of 4 different LC sensors exposed to a specified concentration of NO_2: 1 ppm (red), 2 ppm (green), 3 ppm (blue), 5 ppm (purple) and 7 ppm (black). The black vertical line (time = 0.0 minutes) denotes the moment at which the sensors were first exposed to NO_2. Before the exposure to NO_2, the sensors possess a stable brightness. But within 1 minute of exposure to NO_2, the sensors exhibit a measurable decrease in brightness. The response rate of the LC sensors depends on the concentration of NO_2 in the air stream. This data set demonstrates that it is possible to distinguish between 1, 2, 3, 5, and 7 ppm of NO_2 in the air, as different concentration elicit a different dynamic response of the LC sensor. To further illustrate this point, the percent change in brightness of the LC after 1 minute of exposure to NO_2 is presented in Figure 5, which plots the sensor brightness as a function of NO_2 concentration after 1 minute of exposure. As shown in this figure, greater concentrations of NO_2 lead to larger decreases in sensor brightness after 1 minute of exposure. For example, after 1 min. of exposure to 3 ppm NO_2 the LC sensors exhibited a brightness of 77 ± 5% compared to the unexposed sensors. However, the sensors exposed to 5 ppm NO_2, after 1 minute of exposure, had a brightness of 65 ± 6 % compared to the unexposed sensors. In summary, these results demonstrate that the brightness value and the rate of change in brightness of the LC sensors depend on the concentration of NO_2 at which the sensors are exposed.

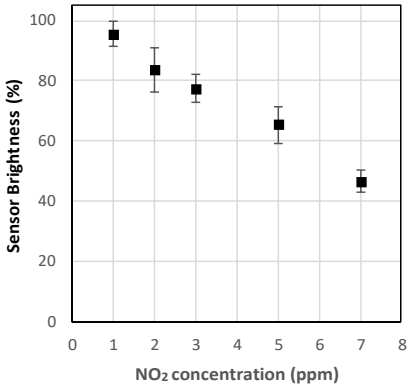

***Figure 5**. Normalized brightness of LC sensors after 1 minute of exposure to NO_2 at concentrations between 1 ppm and 7 ppm.*

3). Exposure to non-target gases: In this section, we present the results of our work, which include the following accomplishments: (a) demonstrated that LC-based sensors exhibit a change in optical appearance upon being exposed to NO_2, but do not exhibit a change in optical appearance upon exposure other non-target gases; and (b) demonstrated that the response of LC-based sensors to 0.5 or 10 ppm of NO_2 is not inhibited by the presence of non-target gases. All experiments described here were carried at room temperature.

In this set of experiments, we explored the optical response of LC sensors to air streams flowing at 200 sccm and containing 100 % air, 10,000 ppm CO_2, 100 ppm CO, 10 % hydrogen (H_2), 100 ppm H_2S, 10% methane (CH_4), 10 ppm SO_2, or 5 ppm NO_2 (Refer to Table 1). These gases were selected for study because they represent the primary gases present in mines, according to the US Mine Rescue Association. The concentration for each gas was chosen as twice the value of the permissible exposure limits (PEL) published by NIOSH. Other than NO_2, the gases listed in Table 1 are referred collectively as non-target gases. As discussed previously, the LC sensors appeared bright when observed through cross-polars prior to any gas exposure. When exposed to NO_2, the appearance of the sensor turned dark, indicative of a change in orientation of the LC molecules. However, the sensors exposed to the non-target gases did not undergo the same transition in optical appearance. The brightness of the LC sensors exposed to non-target gases remained unchanged even after 1 hour of exposure, demonstrating that these non-target gases do not induce a false-positive response of the LC sensors for NO_2.

***Table 1**. Response time and cross-sensitivity of LC-based sensors exposed to NO_2 and other non-target gases. Only NO_2 induces a response in the LC sensor.*

Gas	Concentration used (ppm)	Response time (sec.)	% Cross-sensitivity
Nitrogen Dioxide (NO_2)	**5**	**<1 min.**	**100%**
Carbon Dioxide (CO_2)	10,000	No Response	0
Carbon Monoxide (CO)	100	No Response	0
Hydrogen (H_2)	100,000	No Response	0
Hydrogen Sulfide (H_2S)	5	No Response	0
Methane (CH_4)	100,000	No Response	0
Sulfur Dioxide (SO_2)	10	No Response	0

Next, we determined the effect of non-target gases on the response of LC sensors to NO_2. For this study, the sensors were first exposed to an air stream containing a non-target gas at the exposure concentrations presented in Table 1. After 15 minutes of exposure to the non-target gas, a stream containing NO_2 was introduced continuously into the chamber containing the LC sensor. Thus, the final gas stream contained both NO_2 (at 10 or 0.5 ppm) and a non-target gas in air. As described above, exposing the LC sensors to non-target gases did not induce a decrease in the brightness of the sensors. However, upon introducing NO_2 into the chamber containing the LC, the sensors exhibited a rapid decrease in brightness, even in the presence of the non-target gas. We conclude that the presence of non-target gases does not affect the sensitivity of the LC sensors towards NO_2.

4). Performance of LC sensors at various temperatures and humidity levels: In this section, we present experimental results that demonstrate the following sensor characteristics: (a) air streams containing various humidity levels, but no NO_2, do not induce a false response in the LC-based sensors; and (b) LC sensors undergo measurable optical changes to air streams containing 0.5-10 ppm NO_2 over the temperature range 5-35 °C and 20-80% RH.

In the first set of experiments, we explored the effect of humid air on the observed brightness of the LC sensors. In this experiment, the sensors were exposed for 10 minutes to air streams flowing at 200 sccm and carrying moisture at 0%, 20%, 45% or 80% RH at 22 °C. These streams did not carry NO_2. To produce these streams, an air stream saturated with water vapor was generated by aeration of a water bath at 22 °C. This saturated stream was then diluted with dry air to achieve the desired level of humidity in the gas stream flowing into the LC sensor. The optical response of the LC sensors to the various humidity levels is presented in Figure 6, which shows the plot of normalized brightness of the LC sensors as a function of exposure time to the air stream containing various levels of relative humidity: 0% (blue), 20% (red), 45% (green), and 80% (purple). We note that the sensors not exhibit a change a decrease in brightness, which is only observed when the sensors are exposed to NO_2. Since the water vapor did not lead to a significant and measurable decrease in the brightness of the LC sensor, we conclude that water vapor does not induce a false-positive response in the LC sensors for NO_2.

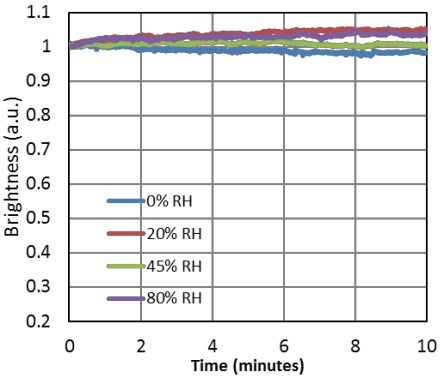

***Figure 6**. Brightness of LC sensors exposed to air streams containing various levels of relative humidity: 0% (blue), 20% (red), 45% (green), and 80% (purple).*

In the next experiment, we studied the response of LC sensors to air streams containing 0.5 ppm or 10 ppm NO_2, and humidity levels of 0%, 20%, 45%, and 80% RH. The LC sensors, optical measuring systems, water bath and gas lines were all placed inside a temperature-controlled chamber set to the desired temperature of 5 °C, 22 °C, or 35 °C. After allowing sufficient time for the water bath, gas streams and LC sensors to equilibrate to the desired temperature, we exposed the LC sensors to 200 sccm of an air stream containing 0%, 20%, 45%, or 80% RH for 8 minutes. Next, NO_2 was mixed with the air streams so that the final concentration of NO_2 in the flow to the LC was calculated to be 0.5 or 10 ppm. The flow of NO_2 into the LC was sustained for 10 minutes, while an optical probe reported the brightness of the LC sensor throughout the duration of the experiment. The LC sensors remained responsive to 0.5 ppm and 10 ppm of NO_2 over temperatures and humidity levels tested. In Figure 7 we present a bar plot of the response time of the LC sensors exposed to 10 ppm NO_2 at temperatures of 5 °C, 22 °C, or 35 °C, and humidity levels of 0%, 20%, 45%, and 80% RH. Note that for all conditions, the sensors consistently respond to NO_2 in well under 1 minute (60 seconds). Nonetheless, we observed a clear decrease in the response rate of the sensors exposed to 0.5 ppm as the temperature humidity of the air stream increased. For example, at 35 °C and 0% RH the brightness of the LC sensors exposed to 0.5 ppm NO_2 decreased by 30% in under 1 minute, but when the sensors were exposed to the same NO_2 concentration at 35 °C and 80% RH, it took ~10 minutes for the brightness of the sensors to decrease by 10%. The mechanism of this humidity-dependent effect is not yet understood, but we anticipate that future approaches will mitigate the effects of humidity on sensor performance.

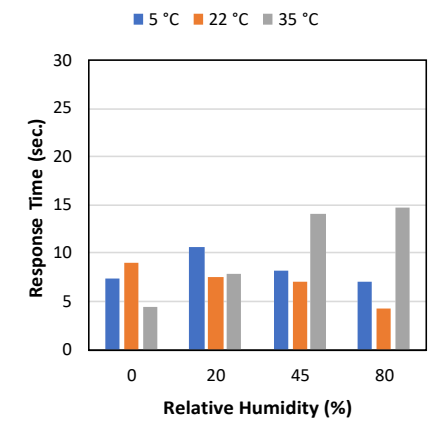

***Figure 7**. Representative response of LC sensors exposed to NO_2 at temperatures of 0 °C, 22 °C, and 35 °C, and relative humidity levels of 0%, 20%, 45, and 80%.*

For example, polymeric humidity barriers that are permeable to NO_2 but not to water could be used in future iterations of the LC sensors to eliminate any humidity effects. In addition, we note that when the LC sensors were exposed to NO_2 at 10 ppm, the response rate was well within 1 minute of exposure even for high humidity levels and temperatures (see Figure 7).

5). Assessing sensor lifetime under storage: In this section, we describe our assessment of the stability of LC-based sensors for NO_2 that were stored for up to 1 month after fabrication. Our work demonstrates that, when property stored, LC sensors retain their sensitivity to 3 ppm NO_2 even after 1 month of storage.

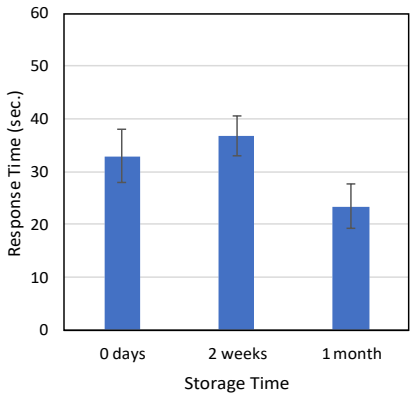

***Figure 8**. Representative response time of LC sensors exposed to NO_2 after storage for various time periods: 0 days, 2 weeks and 1 month.*

Immediately after fabrication, the LC sensors were placed in foil bags and subsequently evacuated and filled with argon gas. The pouches containing 4 LC sensors each were hermetically sealed and stored at 4 °C in a refrigerator for the following time periods: 1 week, 2 weeks, or 1 month. After a pre-determined storage period, the foil bags were removed from the refrigerator and allowed to equilibrate to room temperature (~23 °C) for 15 minutes. Next, the LC sensors were removed from the bags and to an air stream flowing at 200 sccm and containing 3 ppm of NO_2 and 0% relative humidity. In Figure 8 we present the averaged time-dependent response of the different batches of LC sensors that were exposed to 3 ppm NO_2 the same day of fabrication, or stored for 1 week or 1 month prior to NO_2 exposure. As shown in this figure, the average brightness of the sensors decreases rapidly following exposure to NO_2, and within 1 minute of exposure the average sensor brightness decreases from 100% to less than 80% for all three batches of sensors. Note that the LC sensors exhibit a response to NO_2 regardless of the storage time, indicating that the LC sensors remain stable and maintain their sensitivity even after 1 month of storage.

6) Design of electronic monitor: This section presents the design the prototype electronic and mechanical elements that monitor the state of the LC sensor and produce a visual and auditory alarms in response to changes in brightness of the LC caused by the presence of NO_2. The monitor that we have developed effectively converts the chemical reaction of NO_2 with a LC sensor into an audible, vibrational signal with an LED light. The monitor generates a measurable signal based on the intensity of the transmitted light when the LC changes from a planar orientation with a bright appearance to a homeotropic orientation with a dark appearance.

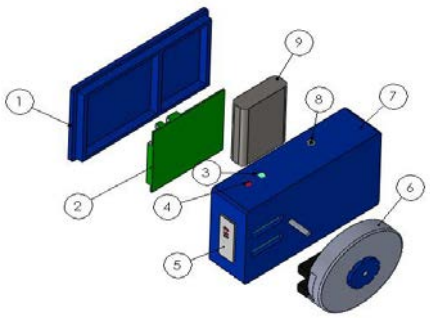

***Figure 9**. Design of electronic enclosure that accommodates LC sensing elements. Exploded view exhibits the following elements: 1) bottom part of enclosure, 2) electronic unit (PCB board with related electronics, 3) power switch, 4) alarm light, 5) level indicator, 6) cap to protect LC sensors from debris, 7) top part of detector enclosure, 8) power connector, and 9) rechargeable battery.*

Multi-load Cartridge Design: To protect the LC sensor elements and facilitate continual use, we house the sensors in a multi-load cartridge which consist of several sealed cavities. Each cavity carries a single sensor. The front and back sides of the cartridge are transparent and made of glass. To use the cartridge, the user removes the protection tape to expose the sensor to any potential analyte. Ideally, the cartridge design carries 8 sensors, however, our current cartridge has just two slots/cavities with sensors. The multi-load cartridge system offers the following advantages: (1) it provides a longer life time for our sensors; (2) it simplifies holding and loading small size sensors; (3) it supports future miniaturization of the sensors; (4) reduces costs by enabling the reuse of the same cartridge.

Monitor Design: Figure 9 displays an exploded schematic view of the monitor for NO_2. The detector has a cartridge holder, rechargeable Li battery, hazardous level indicator, alarm buzzer, alarm light and vibrating alarm. The device provides information about the target analyte and dose, which the user receives during the total time of the sensor's operation. The entire system weighs 91 grams and has the overall dimensions 43mm x 60mm x 100mm. The detector system can provide automatic local monitoring of any target analyte detected by the LC sensor. In **Figure** 10, we present images of the two prototype monitors fabricated by Platypus Technologies. For simplicity, we refer to this technology as RealSense™ NO_2 Monitors. This wearable monitors comprise of a cartridge unit, which held two liquid crystal (LC) sensors and an opto-electronic monitor, which consisted of a light source, light polarizer and analyzer films and phototransistor. We designed the RealSense™ NO_2 Monitor for the automatic detection hazardous levels over 2 ppm NO_2 and for the manual estimate of hazardous level concentrations by using the monitor gas level indicator. The NO_2 concentration is determined from an algorithm that takes into account the signal growth rate, which is proportional to the NO_2 concentration and inversely proportional to the growth rate of the sensor's LC layer thickness. The team set a threshold for the alarm signal at an exposure level of 2 ppm NO_2 flow in a 1-min time frame. In the future, we will design the next generation of the

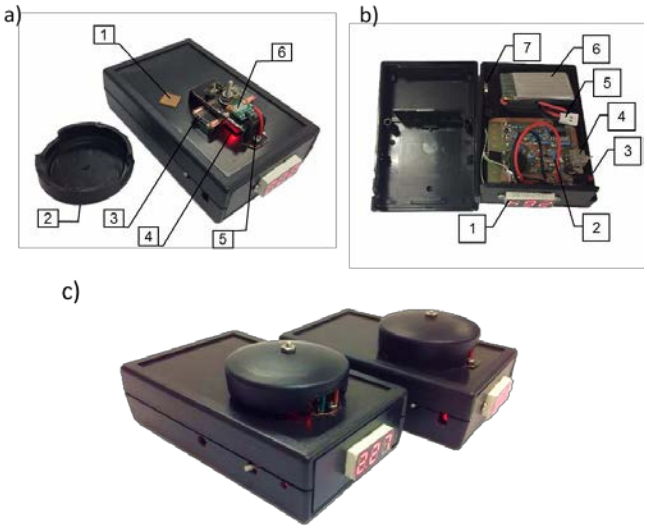

***Figure 10**. Detector view with removed top cartridge cover: sensor removed from the cartridge (1); top cartridge cover (2); cartridge for 2 sensors (3); phototransistor (4); frame (5); and LED (6). Detector view with removed bottom cover: hazardous level indicator (1); PCB board (2); alarm LED (3); power switch (4); power connector for recharging the Li battery (5); Li battery (6) and vibrating motor (7).*

RealSense™ NO_2 Monitor with a new microcontroller and embedded programming that automatically calculates NO_2 concentration based on a new algorithm for the brightness level of the signal and exposure.

To enable easy perception by the users, each prototype included 3 different types of threshold signals: (1) an audio alarm; (2) a visual alarm; and (3) a vibrational alarm. One of the prototype systems had an additional analog output of the voltage measured by the monitor's voltmeter for a computer recording of the monitor's time response.

7) Testing of NO_2 in the lab and in mine environment: In this section, we describe the test results of the RealSense™ NO_2 Monitor in a NIOSH laboratory and in a simulated mine. The two prototype RealSense™ NO_2 monitors were tested at three different locations: (1) Platypus Research Laboratory; (2) NIOSH Test Laboratory; and (3) the NIOSH Safety Research Coal Mine in Pittsburgh, PA. All experiments used a step-like NO_2 gas flow that pulsed with a less than 20 second rise-time. The NO_2 containing gas flow was 0.6L/min and 1.7 L/min at Platypus Lab and NIOSH Safety Lab respectively. All measurements in Labs were performed at room temperature, approximately 20°C (68°F). The test in a coal mine was performed at the temperature of approximately -17°C (-1°F) and NO_2 containing gas flow of 1.7L/min. The volume for enclosures at the Platypus Research Laboratory and at the NIOSH Safety Laboratory were from 2.5mL – 350mL and from 5L – 339L, respectively. Each experimental run conducted at the NIOSH facilities used a Ventis MX4 gas detector produced by Industrial Scientific, as a reference gas monitor.

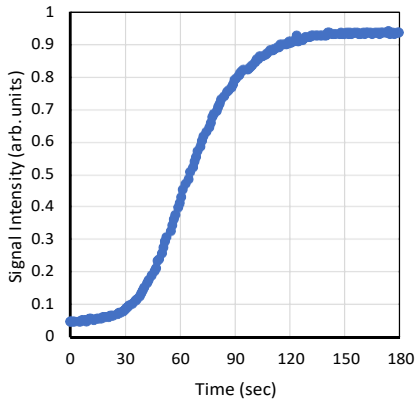

***Figure 11**. Representative response of the NO_2 monitor to a step-lie pulse of the NO_2 gas.*

The variation of the sensor sensitivity measured as a variation of the signal growth rate in response to the step-like NO_2 pulse was approximately ±30%. The team did not observe any remarkable effect of the cartridge on the optical properties of sensors. **Figure 11** displays the response of the Platypus detector to the NO_2 exposure. The data suggests that the sensitivity of the LC-based sensors to NO_2 depends on the molecular transport rate of the NO_2 molecule (e.g. filling the enclosure volume and diffusion through the LC film). Therefore, the Platypus RealSense™ NO_2 Monitor does not need additional calibration as needed by electrochemical or PID sensors.

***Figure 12**. Image of Platypus Technologies team testing the NO_2 sensor in a simulated mine environment.*

As shown in Figure 13, the RealSense™ NO_2 Monitor was tested in a simulated coal mine under subzero conditions. The RealSense™ NO_2 Monitor was exposed to 5ppm NO_2 flowing at 1.7 L/min at approximately –17°C. The RealSense™ NO_2 Monitor alarmed within 45 seconds after exposure.

Test of the RealSense™ NO_2 Monitor were also carried in the NIOHS Safety Laboratory against a Ventis MX4 reference monitor. Two test were carried and in both cases the RealSense™ NO_2 Monitor responded faster than the Ventis MX4 monitor.

Conclusion:

Platypus Technologies has developed a person-wearable monitor for NO_2. The current prototype monitor comprises a sensing elements that detects NO_2 via optical transitions in LCs that do not require electricity. In addition, an electronic device reads the state of the LC, and provides a visual alarm to the user of the presence of NO_2. The Platypus prototype RealSense™ NO_2 Monitor demonstrated competitive performance in NO_2 detection against the commercial Ventis MX4 gas detector in both laboratory and simulated mine tests at NIOSH. The prototype displays key advantages, which warrant its continued development and support its commercial viability as an effective tool that can reduce the exposure to deleterious levels of NO_2. The key value of proposition of the RealSense™ NO_2 Monitor includes:

- High sensitivity, short response time and wide detection range
- Lightweight, compact design, portable and designed for personal use
- Highly resistive to shocks, humidity, and temperature variations
- Sensors elements do not need electrical power for heating or biasing
- Highly selectivity to NO_2, and no interferences with other gases
- Provides hazardous level information, alarm light, audio signal and vibration
- Uses rechargeable battery with operating time of more than 8 hours before the next recharging
- Uses multi-sensor cartridge loaded with one-time-use inexpensive sensor elements
- Cartridges allow quick exchange of sensors and increases sensor life-time
- Low manufacturing cost.

Future Work:

Platypus Technologies has made tremendous progress in the past year regarding the development of a personal monitor for NO_2. The RealSense^{TM} NO_2 Monitor by Platypus offers an affordable solution to enable mining companies to equip every worker with a personal monitor and thus reduce risks of overexposure to NO_2. In order to bring the technology to the market, however, the device needs further development and real-world, robust testing.

The technological challenges that need to be addressed include: (1) sensor-to-sensor variations; (2) detection of low concentrations of NO_2 in high humidity environments; (3) extended lifetime of the sensor elements; (4) better correlation between LC sensor response time and monitor output; (5) integrate human factors considerations into the design of the sensor. These challenges can be readily addressed with standard manufacturing and chemical approaches, and we are confident that, with additional support and time, we can address these challenges. Accordingly, Platypus Technologies will be preparing an application in response to the Broad Agency Announcement that will provide the funding necessary to resolve the remaining technical issues, conduct additional tests in real world conditions, and set the course for the commercial launch of the product through its technology and manufacturing partners.

Appendix A: Human Factors Considerations for the Platypus Personal NO_2 Monitor

By: Jonisha Pollard – jni3@cdc.gov

The Platypus liquid crystal NO_2 monitoring system (designed under BAA 2013-N-14974) is designed to be person-wearable and provide an indication of the concentrations of NO_2 in the environment. The device was light-weight and very easy to wear. While the goal of this sensor was to measure and display NO_2 concentrations, the intended use was not well defined at the time of review. There are several areas of design and usability which should be considered from a human factors perspective to ensure that the device is usable in an underground mining environment.

1. Purpose of monitoring – The current version of the device is capable of displaying instantaneous readings and as described can also provide some differential or integrated values. The purpose of these differing types of measures should be decided and the intended actions of miners in response to these readings should be better defined. If the purpose of the device is to alert the miner of high concentrations of NO_2, then the device should display the concentrations and be capable of having some type of display/alarm which gets their attention. Also, in this situation, the displayed results should be instantaneous readings, allowing a miner to use the readings to safely remove themselves from the hazardous environment. The purpose of the cumulative exposure readings was not well explained and it remains unclear if that is a necessary feature.

2. Sensor health – The current version of the device does not have a means to determine the status of the liquid crystal sensor. It was stated that the sensor could be used for a week, but could also be replaced daily. There isn't a way to look at the device and determine how long the sensor has been used, if the sensor has had a triggered alarm, or any other necessary information. The next prototype should include some display or metric that allows a miner to look at the outside of the device and determine when the sensor should be changed. The usage requirements for the device could also be more concrete such as requiring the replacement of the sensor daily after use, and automatically switching to a new sensor when an alarm is triggered.

3. Alarm mechanism – The current version of the device features a small red LED, an audible continuous tone, and vibration to alert the miner when an alarm is triggered. These mechanisms should be reconsidered to improve their detection by a miner who may be operating loud, vibrating equipment while wearing this device with the LED located outside of their direct line of sight. The primary means of alarm should be visual followed by auditory. The visual alarm should be located within the miner's line of sight. The current device is designed to be worn on the front of the body at chest level. As such, one option for the visual alarm would be to provide a wider hazard display area by installing a series of LEDs with some level of offset (such as every other on) around the outside of the monitor. When an alarm is triggered, the miner would be alerted by the appearance of the moving lights and could then check the device to determine the levels. An auditory alarm should also be used and would need to incorporate a temporal pattern. The alarm tone should be designed to not mimic or closely resemble any other alarms which are already present in the mining environment. The alarm will also need to

be loud enough to be heard over mine noise and when wearing earplugs; at least 10-15 dB higher than the ambient noise.

4. Intuitive design – Overall the device should be intuitive and should not require significant training to use or maintain. All information from the device should be directly readable from the screen without any computations by the miner. If this device will display instantaneous and cumulative exposure levels, it should be clearly indicated which level is being presented. The device should also include "NO_2" near the display line so miners are clear what the device is detecting.

For more information, please refer to the Handbook of Human Factors in Medical Device Design, by Weinger, Wiklund, and Gardner-Bonneau published by CRC Press in 2010.