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Multi-Hazard Sensor for Minors

Phase I Final Report

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LIST OF TERMS AND ABBREVIATIONS

TDLAS – Tunable Diode Laser Absorption Spectroscopy

WMS – Wavelength Modulation Spectroscopy

1. Abstract

NIOSH conducts activities to assure safe and healthful conditions for American workers. The mining industry presents particularly challenging safety and health needs. Miners are continuously exposed to methane, carbon monoxide, hydrogen sulfide, diesel fumes and particulate matter including coal dust. At low concentrations, chronic exposure to these airborne hazards can cause miner health problems, but at high concentrations the hazards are immediately life threatening due to their toxicity and potential for explosion. Thus, there is a need for technology able to measure the exposure of miners to these hazards *as well as to warn miners of immediately dangerous conditions within or prior to entering potentially hazardous areas.*

This Research and Development project will lead to the development of a novel technology platform enabling laser-based sensor products to detect and measure these hazards from a distance. The sensors will warn miners prior to entry into a potentially explosive or toxic atmosphere, as well as monitor for hazards in physically inaccessible areas, simplifying mining operations and enhancing productivity. Currently, miners use cumbersome techniques that require sampling and analyzing mine air to sense these hazards. New laser-based techniques, developed by Physical Sciences Inc. (PSI) and now being adopted by the natural gas and other industries, enable sensing explosive or toxic environments from afar by illuminating the region of interest with a laser beam. To bring this technology to the mining industry, this project is intended to result, after Phases 1-3, in a novel suite of products that provide quantitative *standoff* sensing of the airborne mining hazards.

Two technologies that PSI has previously developed into robust compact industrial sensor products form the foundation for the proposed miner safety sensor suite. These underlying technologies are standoff Tunable Diode Laser Absorption Spectroscopy (TDLAS) and laser Mie scattering. Using a transceiver similar in form to a handheld or helmet-mounted headlamp, the sensors illuminate an area with near-infrared light, projecting an eye-safe laser beam through airborne particles and onto mine walls and structures. Optical components within the transceiver or a companion receiver collect some of the laser light diffusely scattered from the walls and particles. Signal processors on battery-powered circuit boards analyze the collected laser light and determine the concentrations of each hazard along the path of the laser beam. Real-time audible alarms warn of immediate or imminent danger.

Phase 1 demonstrated the feasibility of applying these technologies to measure hazardous concentrations of CO, CH_4, and dust with a sensor that is convenient for a miner to carry. That project, described in this report, provided a foundation for Phase 2. The Phase 2 Specific Aims are to: 1) design and engineer a novel multi-hazard sensor product platform architecture that simplifies configuring sensors to address a variety of mine safety needs; 2) demonstrate and evaluate the technology in test mines or operational mines; and 3) communicate results with the mining industry.

2. Highlights/Significant Findings

The overall Phase I objective was to demonstrate the feasibility of developing the envisioned suite of miner safety sensor products. The Phase I specific aims were to:

1) Demonstrate the feasibility of adapting standoff TDLAS technology to sensing methane and carbon monoxide concurrently in a configuration suitable for helmet mounting and with the sensitivity and standoff distance appropriate for miner health and safety.

2) Evaluate the feasibility of adapting laser Mie scattering technology to helmet-mounted standoff sensing of explosible airborne particulate matter.

The Phase I project was structured as a series of Tasks intended to achieve the following milestones:

1) Confirm with potential users the preliminary specifications of the sensor suite
2) Build a prototype compact optical transceiver meeting the critical specifications for helmet mounting
3) Demonstrate ability to measure both methane and carbon monoxide
4) Define and model configurations of the explosible particle sensor
5) Build and evaluate a breadboard particle sensor

All milestones were achieved successfully.

Phase 1 demonstrated the feasibility of building compact laser-based instruments that continuously and remotely probe the environment for multiple hazards and provide early warning of immediately dangerous conditions prior to miners entering a hazardous area. Phase 1 also taught that there are additional miner safety applications of the sensing technology. These include monitoring for explosive gas accumulations within sealed and other inaccessible mine areas, inspecting new mine face walls for methane sources, as well as monitoring for toxic gases in active mine regions. Current techniques, using Combustible Gas Indicators for example, require use of a probe that physically enters the area of interest and withdraws a gas sample through a hose that dilutes the sample and delays the analysis. Our laser-based standoff sensors require only that a laser beam illuminate the sampling area. They rapidly readily scan wide areas and provide instant analysis, thereby offering the opportunity to simplify mining procedures while enhancing miner safety.

3. Translation of Findings

Several general themes emerged from the Phase I research findings:

- Miner safety is a high priority of mine operators.
- Regulations (e.g. Title 30 Code of Federal Regulations) are in place for protecting mine safety, and these regulations dictate required measurements, measurement equipment and procedures.
- A helmet-mounted sensor is not necessarily the preferred configuration. Handheld units, permanently-installed devices, or units that mount on mining vehicles, may be preferable for some uses.
- Within the US, existing sensing equipment, measurement procedures, and ventilation techniques are successfully precluding explosions in active mining areas. However, explosion hazards exist in inactive regions that are poorly ventilated and not monitored. These regions include sealed areas, called gobs, as well as caverns in mine ceilings where methane can accumulate. In both cases, methane accumulations can explode when triggered by a spark. In the 2006 Sago (WV) mine disaster, a methane-filled gob exploded when triggered by a nearby lightning strike.[1] Explosions of methane trapped in ceilings can be triggered by a spark from an electrically-powered trolley. In this case, a fast sensor that detects the hazard and shuts off electricity is of value.
- Laser-based sensors may enhance efficiency of current gas sampling techniques. For example, in the "room and pillar" mining technique, miners digging a new room must inspect for venting methane along the face wall at the back of the room. Inspection currently utilizes catalytic or thermal conductivity technologies (combustible gas

indicators or explosive gas meters) that must draw gas samples from the region of interest. Sampling is via a probe on a long pole or attached to a hose. This is a difficult sampling process, with excessive time lag between sampling and analysis causing a high probability of missing vents. A standoff laser sensor can simply scan the laser beam across the face wall to locate vents.

- For mine operators to readily adopt new technologies, the technology must be better and less costly than the incumbent, and must operate within the constraints of the regulations.
- New technologies providing capabilities not covered by existing regulations are desirable but, before they will be widely accepted for use, their value to the operators must be demonstrated and regulations for their use must be established.

30 CFR 75.351 specifies means and locations for installing and operating CH_4, CO, and smoke sensors in coal mines. While not specifically excluded, current regulations do not readily embrace standoff sensing of explosion hazards. Therefore, though it is a technology that potentially offers significant health and safety benefits, to gain acceptance by the mining industry the PSI multi-hazard sensor suite needs to be developed, proven, and written into regulations.

This work revealed that the multi-hazard sensor platform offers capability to address several mine safety applications, each requiring a unique optical configuration and method of use. Thus, a principal outcome of Phase I is the recommendation that, rather than focus on the helmet-mounted configuration addressed in Phase I, the Phase II project should emphasize development and demonstration of a configurable technology platform.

4. Outcomes/Relevance/Impact

Phase 1 demonstrated the feasibility of building compact laser-based instruments that continuously and remotely probe the environment for multiple hazards and provide early warning of immediately dangerous conditions prior to miners entering a hazardous area. Phase 1 also taught that there are additional miner safety applications of the sensing technology. This work provided a foundation for a Phase II project wherein PSI, collaborating with academic, government, and industrial mining and instrumentation experts, intends to develop an innovative flexible technology platform for standoff sensing of airborne explosive and toxic gas hazards specifically to address mine safety needs. This platform enables combining building block components to configure customized mine safety sensor products that address site specific hazard sensing requirements. A successful Phase II project will not only lead to commercial products that enhance miner safety, but the technology platform will have additional non-mining combustible gas sensing applications. These include fire safety, chemical processing, defense, security, and law-enforcement uses.

In recent years, accidental explosions have caused hundreds of coal miner deaths worldwide. As competition for oil resources increases, the importance of coal as an American fuel will grow, as will the importance of mining it safely and efficiently. New mining safety equipment and procedures will help keep coal affordable. The laser-based standoff multi-hazard sensors can help modernize and simplify coal mining safety procedures as they have in natural gas leak surveying. Unlike current practices that require drawing gas from the sampled area to evaluate its hazardous gas content, laser-based standoff sensors require only that a laser beam illuminate the sampling area. They rapidly readily scan wide areas and provide instant analysis. They thereby offer the opportunity to simplify mining procedures while enhancing miner safety. The technology developed for mine safety will also advance the state-of-the art for gas sensing by TDLAS, enabling reduced cost delivery of custom configurations serving many applications, which include opportunities for academic research addressing safety.

5. Scientific Report

5.1 Background

Despite well-regulated safety procedures, accidental explosions and toxic gas inhalation continue to cause coal miner deaths around the world. To help prevent such tragedies, advance warning technologies are needed that sense and measure, from a distance, concentrations of explosive or other life threatening hazards including methane (CH_4), carbon monoxide (CO), hydrogen sulfide (H_2S), and particulate matter.[2] Table 1 shows that at low concentrations chronic exposure to these airborne hazards can cause miner health problem, but at high concentrations the hazards can be deadly due to their toxicity and potential for explosion.[3] This Phase 1 SBIR project demonstrated the feasibility of developing a novel integrated, compact, lightweight, and low power sensor product that provides fast, quantitative, **standoff** sensing of mining explosion hazards. Two technologies that PSI has previously developed into robust compact industrial sensor products enable sensing hazardous gases and particles. These underlying technologies are standoff Tunable Diode Laser Absorption Spectroscopy (TDLAS)[4-6] and laser Mie scattering.[7]

Table 1. Airborne Hazards to Miners

	Explosive Concentration	Acute Inhalation	Chronic Inhalation (8-hr limit)
CH_4	5%		
CO	12.5%	1200 ppm	35 ppm
CO_2		>0.5%	
O_2		<19.5%	
H_2S	4%	100 ppm	10 ppm
Dust	10 g/m^3	25 mg/m^3 SiO_2	1mg/m^3
Diesel		1750 mg/m^3	3.5 mg/m^3

5.2 Phase I Specific Aims

The overall Phase I objective was to demonstrate the feasibility of developing the envisioned suite of miner safety sensor products. The Phase I specific aims were to:

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5.3 Procedures, Methodology, Results and Discussion

Milestone Summary

The Phase I project was structured as a series of Tasks intended to achieve the following milestones:

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2) Build a prototype compact optical transceiver meeting the critical specifications for helmet mounting

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All milestones were achieved successfully, as described below.

Task 1 – Compile and Confirm Preliminary Specifications

Prior to Phase I, we compiled a set of preliminary specifications for the envisioned multi-hazard sensor suite. These specifications were based on available literature describing miner hazards combined with knowledge of sensor capabilities. In this Task, PSI and our commercial partner, Heath Consultants Inc. (PSI's licensee of the Remote Methane Leak Detector) contacted and met with several representatives of the mine safety community, including mine operators, equipment suppliers, and researchers. We discussed and solicited feedback on the sensor concept, preliminary specifications, and development plans. Several general themes emerged from these conversations:

- Miner safety is a high priority of mine operators.
- Regulations (e.g. Title 30 Code of Federal Regulations) are in place for protecting mine safety, and these regulations dictate required measurements, measurement equipment and procedures.
- A helmet-mounted sensor is not necessarily the preferred configuration. Handheld units, permanently-installed devices, or units that mount on mining vehicles, may be preferable for some uses.
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Task 2 –Tunable Diode Laser Absorption Spectroscopy (TDLAS) for Hazardous Gas Sensing

In this Task, PSI:

- Modified a TDLAS Wavelength Modulation Spectroscopy (WMS) Control Unit, and combined it with a second unit, to provide simultaneous measurement of CH_4 and CO
- Designed and built a compact standoff transceiver suitable for miner helmet mounting
- Combined the transceiver with the dual-gas WMS system, and
- Demonstrated simultaneous standoff measurement of CH_4 and CO mixtures

Dual-gas TDLAS

To measure CH_4 and CO simultaneously, we built a frequency-multiplexed TDLAS[8] analyzer using two WMS Control Units, as illustrated by Figure 1. Frequency multiplexing is the essence of virtually all broadcast telecommunications systems; it is the process of concurrently transmitting several signals of different frequencies, and then tuning a receiver to analyze one selected signal. Of course, several receivers may analyze several signals simultaneously.

Frequency multiplexing is implemented in WMS by selecting a unique frequency for modulating and demodulating (by phase-sensitive or lock-in amplification) the laser signal corresponding to each target gas. Each Control Unit transmits a laser beam at a wavelength suitable for detecting its target gas. The Control Units modulate the two lasers at modulation frequencies distinct from each other. A fiber optic coupler combines the two laser beams onto a single optical fiber that transmits the laser light to the transceiver. The photodetector converts scattered laser light received by the transceiver into an electrical signal containing the two distinct modulation frequencies. Spectral absorption by the target gases creates harmonics of the modulation frequencies. The lock-in amplifier in each controller accurately measures the amplitudes of the fundamental and second harmonic frequencies generated by the laser the controller modulates, and is insensitive to the modulation frequencies of the other laser. The ratio of second harmonic amplitude to the fundamental amplitude, multiplied by a calibration constant, yields the target gas concentration.

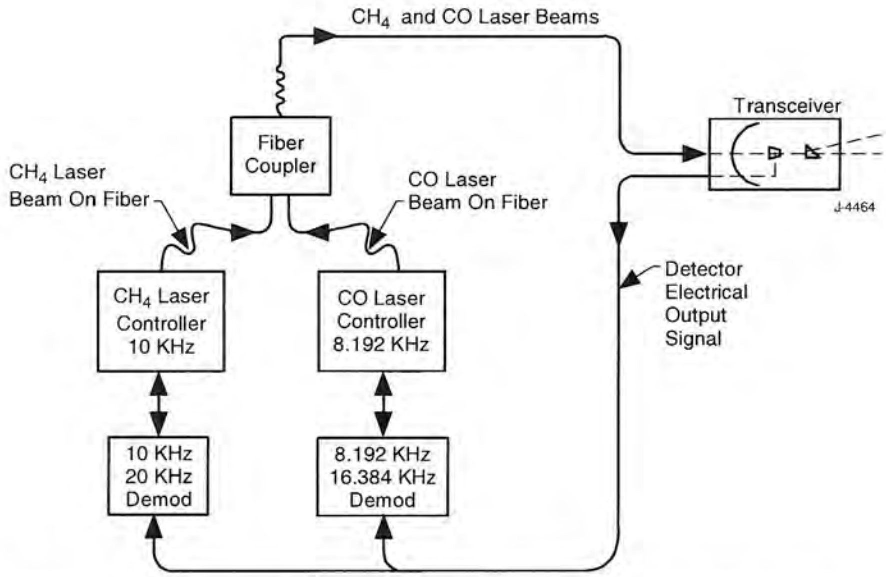

Figure 1: Two gas frequency multiplexed TDLAS configuration.

In this Task, we assembled and tested a laboratory prototype two-gas frequency multiplexed TDLAS system. The system used two PSI single-board WMS units, pictured in Figure 2. One unit sensed methane (CH_4) using a 1652 nm laser, the standard wavelength used in our RMLD product. It provided sensitivity (i.e. noise-equivalent detection limit) of about 5 ppm-m, which is overly sensitive for miner safety applications. (Future versions will utilize a weaker methane absorption line, such as 1518 nm). The other unit sensed carbon monoxide (CO) at 1583 nm. This CO wavelength was selected to utilize a laser that was already available in our laboratory and provides a sensitivity of about 2000 ppm-m CO, corresponding to a noise-equivalent detection limit of 100 ppm over a 20 m path. This sensitivity is appropriate for miner safety applications. A fiber coupler combined the optical output power of the two lasers. We modified the modulation frequency of one TDLAS/WMS unit from its standard 10 kHz to 8.192 kHz. This required alteration of both the firmware that establishes the modulation frequency and the electronic hardware that filters unwanted higher harmonics of the fundamental frequency. The transceiver's photodetector output signal was inputted to the demodulation and data processing portions of both WMS units.

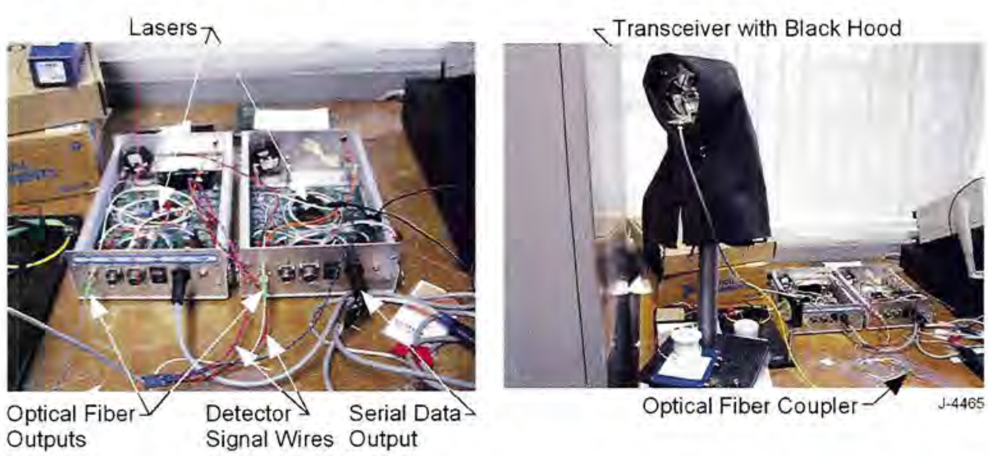

Figure 2: Photographs of dual WMS Control Units.

The processed information was outputted from each WMS board via a serial RS-232 digital data stream. The data stream provided one line of data every 100 ms, a 10 Hz data rate. To record these data on a laptop computer that has only one available RS-232 port, the CO data stream was converted to USB format. The USB port and LabWindows software that we utilized in this Phase I project was, unfortunately, unable to capture the data at the 10 Hz rate, thus the recorded CO data was temporally discontinuous. This inconvenience will be corrected in Phase II and has no significant impact on the successful Phase I accomplishments.

Compact Transceiver

Complementing the dual-gas Control Units, PSI designed, built, and utilized an optical transceiver with size and weight making it compatible with mounting on a miner's helmet. Design goals were a height of 6.6 cm and length of 10 cm. Figure 3 illustrates the design achieved, which utilizes several components from the commercial RMLD transceiver.

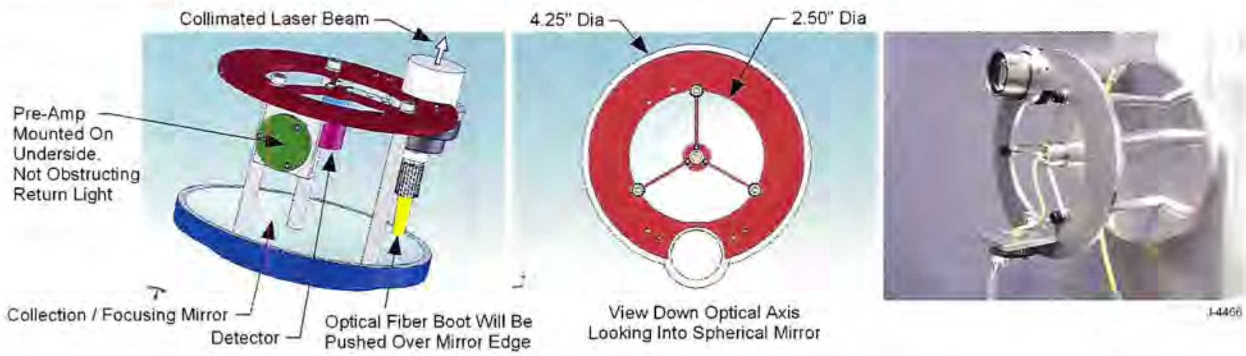

Figure 3: Solidworks drawings and photograph of the compact transceiver.

The transceiver combines a fiber-coupled collimated laser transmitter with a Cassegrain-style telescope receiver in a single compact package. The transmitter portion is a commercial (Oz Optics) collimator comprising a short focal-length lens and an FC-style optical fiber connector in an integrated housing. The collimator projects the laser beam along a path nearly parallel to the receiver optical axis. The laser beam is axially symmetric and diverges with a nominal 0.05 rad angle. The receiver portion has a clear aperture of 6.25 cm and a single collection mirror of 50 mm focal length. A 1.5 mm diameter InGaAs photodetector is located at the mirror's focus. A single-board transimpedance amplifier is mounted near the photodetector but outside of the optical path. The amplifier output is the input to the WMS signal processing hardware. When in use, an opaque material surrounded the transceiver sides to shield the photodetector from stray light.

System Test

We tested the functionality of the dual-gas WMS system and compact transceiver using the configuration illustrated by Figure 4. We aimed the transceiver at an optical measurement cell target built from a tubular bucket, 25 cm in diameter and 25 cm deep. The rear surface of the cell (i.e., the bottom of the bucket) was painted white, the sides were painted black, and the front was sealed with a pane of glass. Gas inlet and outlet tubes were attached via Swagelok fittings to the bucket walls. We positioned the bucket approximately 10 m from the transceiver and directed the laser beam to illuminate the center of the rear surface.

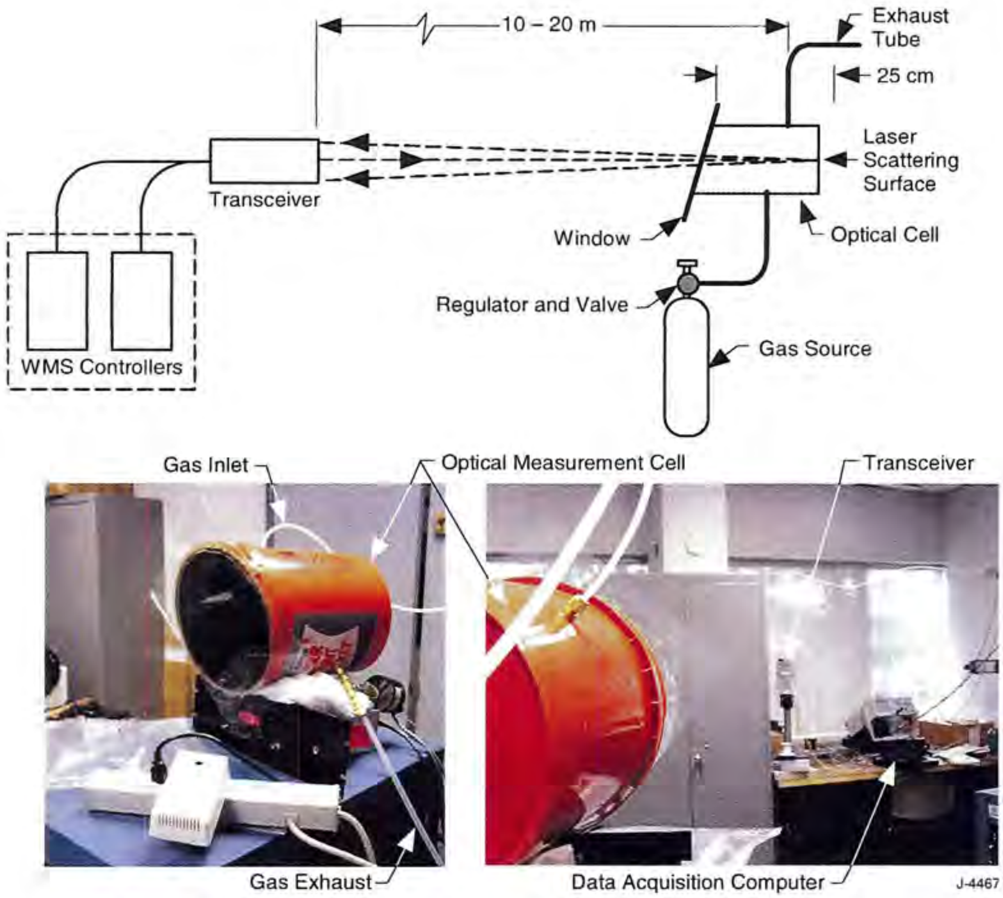

Figure 4: Configuration and photographs of test apparatus.

Figure 5 presents data showing that there is no measurable crosstalk or interference between the two gas measurements. The upper plot shows the signals called F1, which are proportional to the amplitudes of the laser power received at each fundamental modulation frequency. It is, in essence, a measure of the power received from each of the two lasers. The lower plot shows the measured concentration of each gas. At the beginning of data acquisition, both lasers were operational and interrogating the measurement cell, which was filled with uncalibrated concentrations of CH_4 and CO. Near Point No. 600 (60 seconds after start), we disconnected the CO laser's optical fiber. Thus, the F1 signal for that laser diminished to zero. We re-connected the fiber near Point No. 1050, and then disconnected the CH_4 fiber near Point No. 1350. The CH_4 fiber was reconnected near Point No. 1700. ***The data show that disconnecting one laser has no measurable effect on the measurements made by the other laser***, as intended. (Note that the concentration reported when a laser is disconnected is noisy but has no meaning. The system reports an error for the disconnected laser.)

Figure 6 shows concurrent measurement of the two gases. In this case, we initially filled the cell with a mixture of nominally 5000 ppm CH_4, 10% CO, and the balance N_2. We then flushed the cell with 100% CO. During the flush, the CO concentration increased while the CH_4 concentration decreased. We stopped the flush when CO concentration reached approximately 50% and the CH_4 concentration decreased to about 45% of its initial value due to the CO dilution. ***This measurement verifies that both gases are measured simultaneously and the measured concentrations do not interfere with each other.***

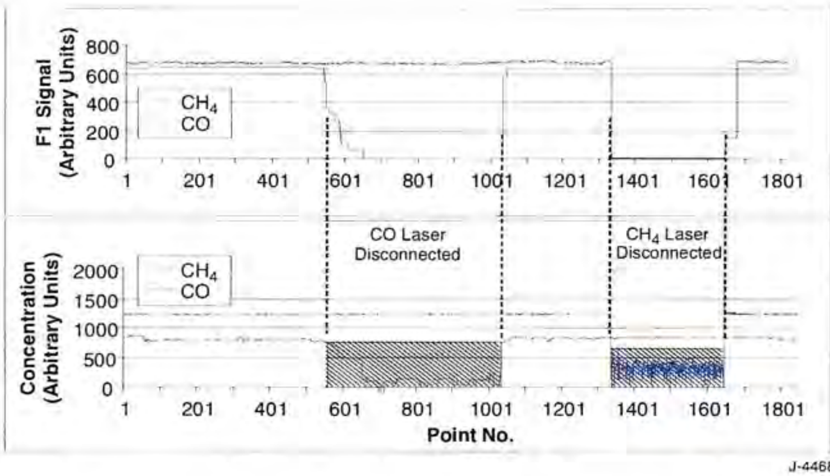

Figure 5: F1 and concentration values recorded while sequentially disconnecting and re-connecting each laser.

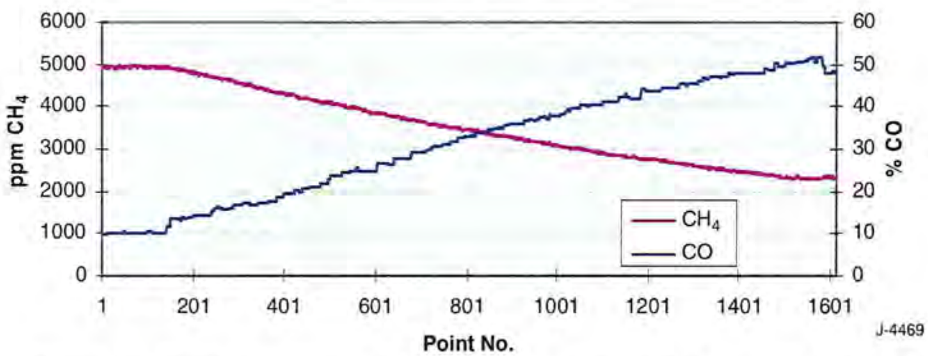

Figure 6: Dual gas concentrations measured as CO flushes the cell.

Figure 7 shows the concentrations of the two gases after filling the cell with high concentrations of each and then flushing the cell with N_2. As the N_2 flows, the concentrations of both gases decreases exponentially (i.e. $C(t) = C_oe^{-at}$). Therefore, a semi-log plot of concentration vs time (or Point No.) yields a straight line. Figure 10 shows that both gases follow such a straight line for at least two orders of magnitude, ***thus demonstrating response linearity for each of the two gases***. (Note that prior to Point 250 the CH_4 concentration is high enough to nearly saturate the data processor and is thus non-linear and noisy).

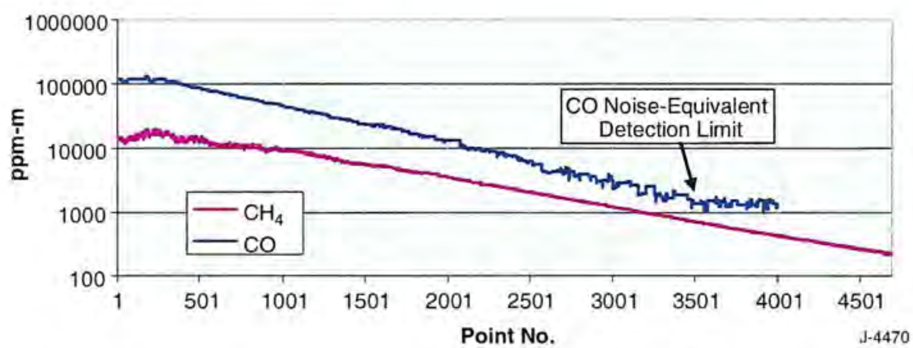

Figure 7: Dual gas concentrations measured as N_2 flushes the cell.

Task 3 – Laser Mie Scattering for Sensing Dust and Diesel Particulate Matter

In this task, PSI:

- Theoretically modeled the laser power backscattered by particulate matter and received by the sensor
- Used the results to calculate expected sensor sensitivity to dust and diesel particles, and
- Validated the calculations experimentally.

<u>Sensor Model</u>

The laser power, Φ, received by the scattering sensor due to backscatter from suspended particles is determined by characteristics of the particles and the optical configuration:

$$\Phi = P\sigma\rho LA/R^2 \quad (1)$$

where:

P = laser power incident on the particle cloud, (W)

σ = the scattering cross-section, (m^2/g-sr), a function of particle size, optical refractive index, laser wavelength, and scattering angle, as described below

ρ = mass density of the particle cloud, (g/m^3)

L = observable length of laser beam that intercepts particles, (m), a function of the separation between laser transmitter and receiver, and receiver field-of-view

A = is the area of the sensor's receiver optic, (m^2)

R = the standoff distance between receiver and particles, (m)

We predicated the receiver optical configuration on tradeoffs between optimizing sensitivity to scattering from particles vs standoff range, while rejecting light scattered from the wall behind the particle cloud. We selected a configuration where the transmitted laser beam intercepts the receiver optical axis (the "crossing point") at a range of R = 5 m, and the lateral separation between transmitter and receiver is 20 cm, illustrated by Figure 8. Combining a receiver optic having 5 cm focal length with a detector having a 1.5 mm diameter yields a 15 cm diameter field-of-view at the 5 m standoff range. The portion of the laser beam within the observable field-of-view extends approximately 3.75 m (= L/2) in each direction away the crossing point. Thus, the wall can be anywhere beyond about 4 m from the crossing point, or 9 m from the sensor. Like the gas sensor, the receiver optic has a diameter of 6.25 cm, yielding A = 0.0123 m^2.

To calculate mass-specific scattering cross-sections, σ (m^2/g-sr), we employed a PSI Mie scattering code.[9] The calculation requires knowledge of particle refractive index. For coal particles, Figure 9 plots real and imaginary values of refractive index vs coal H/C ratio, deduced from an empirical relationship.[10] Our calculations assume a nominal H/C ratio of 0.7 and a coal density of 1.35 g/m^3. For diesel (soot) particles, our calculations utilize the optical properties detailed by Dobbins and Megaridis.[11] Figure 10 plots sample results of these cross-section calculations for detection at 180° backscatter.

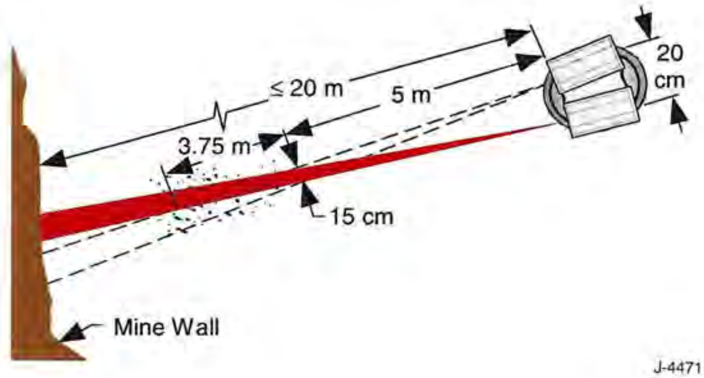

Figure 8: Configuration of model particle sensor (not to scale).

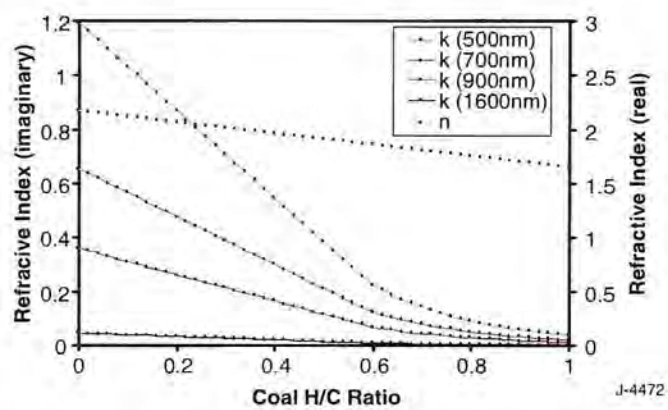

Figure 9: Refractive indices for coal versus hydrogen/carbon content.

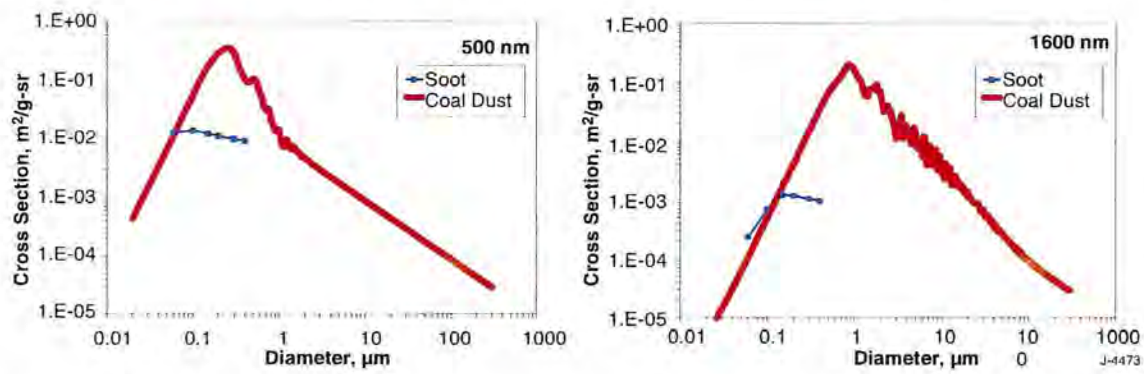

Figure 10: Calculated coal and soot particle mass-specific backscatter (180°) cross-sections versus particle diameter for two different wavelengths.

To complete the calculation of power received by backscattering from particle clouds, we utilized particle cloud mass densities (ρ) from literature describing explosive and respiratory hazards. Figure 11 plots explosive limits for coal dust in the presence of methane. We note that because the explosive limit depends on the combination of dust and methane concentrations, *the dual gas and particle sensing capability of the multi-hazard sensor can potentially yield a more accurate determination of the explosibility of the interrogated environment.* The NIOSH IDLH value for diesel particulate matter is 1.75 g/m^3.

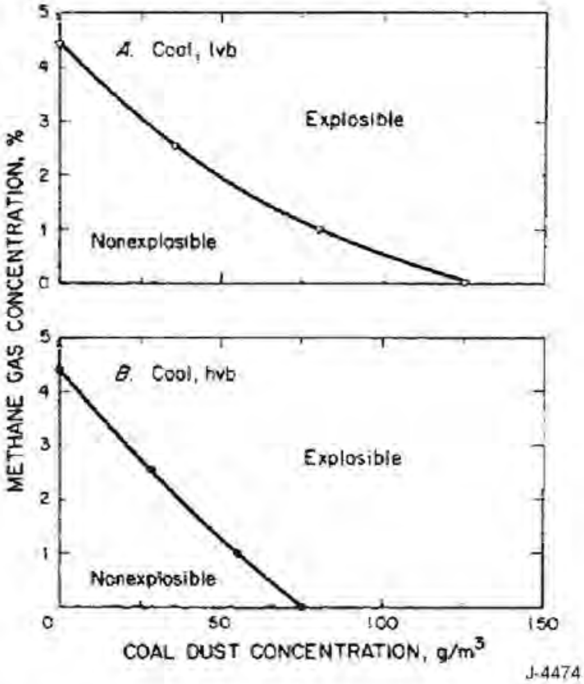

Figure 11: Explosive limits of coal dust aerosol versus coal dust and methane concentration.[12]

Figure 12 shows the model sensor's received laser power vs coal particle size and mass loading, calculated assuming a 10mW laser at 1600 nm. For 20 µm particles, at least tens of nW will be received. *This power level is readily detectable using narrow-bandwidth filtering techniques such as lock-in amplification.*

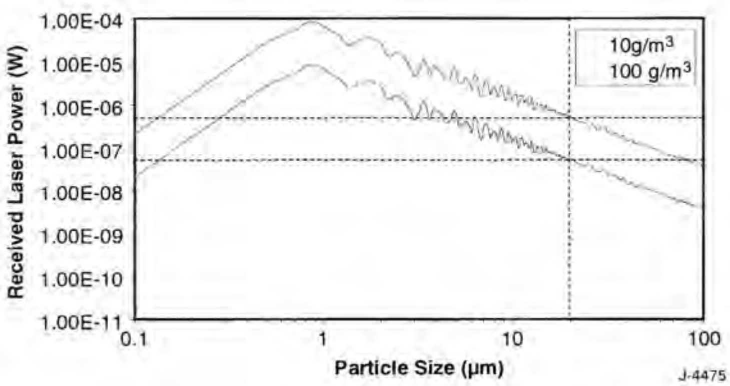

Figure 12: 5m standoff conceptual scatter sensor signal versus particle size for 10 and 100 g/m^3 coal dust aerosol density. Laser source is 1600 nm and 10 mW.

Diesel soot particles at the IDLH level of 1750 mg/m^3 will yield receiver power levels of about 15nW, also readily detectable. *Thus, the scattering sensor is expected to provide standoff detection of all acutely hazardous scenarios.* However, the low particle concentrations (<0.01 g/m^3) that present chronic breathing hazards are not likely to be detectable with this sensor technique, and we give no further consideration to using the sensor for this purpose.

It is notable from Figure 13 that the ratio of coal particle scattering cross-section to that of diesel particles changes by an order-of-magnitude as wavelength changes from 1600 to 500 nm. *This observation suggests the possibility of determining particle type using a two-laser scattering technique.* Unfortunately, we were unable to further pursue this concept within the constraints of this Phase I project.

Experimental Verification

We verified the backscattered power calculation experimentally with a small benchtop particle cloud enclosed in a fishtank-style glass chamber, illustrated by Figure 13. We utilized the gas sensor transceiver described by Figure 3. The chamber was positioned 5m from the transceiver and at a 60° off-normal angle to preclude detection of reflections from the glass. The optical path within the chamber was 34 cm. Light transmitted through the chamber was absorbed by a beam trap. We installed a set of fans within the chamber to circulate dust.

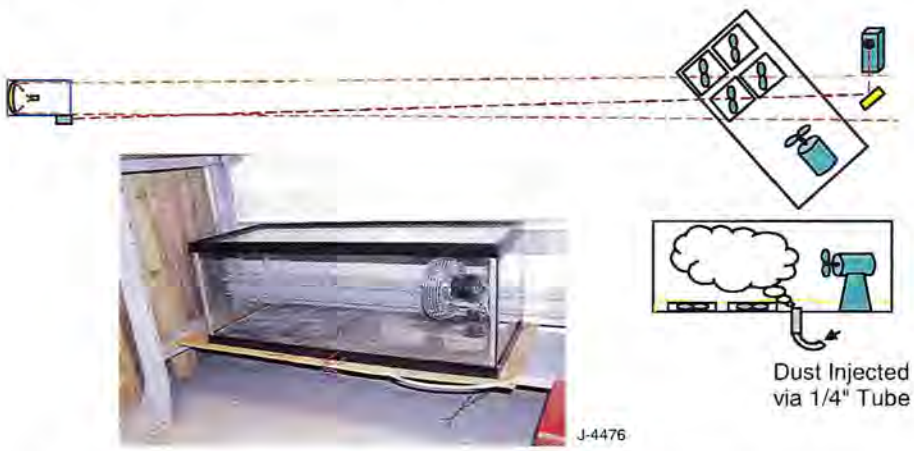

Figure 13: Schematic of dust aerosol sensing experimental setup.

To create a dust cloud and measure light scattering signals, with fans running we injected into the chamber measured masses of aluminum oxide powder screened by a 240 mesh sieve (particles ≤ 63µm). The dust quickly dispersed throughout the chamber, yielding an initial mass density equal to the injected mass divided by the chamber volume (0.063m^3). Despite continual air circulation within the chamber, the particle loading rapidly diminished after injection due to particles sticking to surfaces or becoming trapped in areas free of circulation. Injected particle masses ranged from 0.5 to 5g, yielding initial mass densities of 8 to 80 g/m^3. Because we observed only 34 cm of optical path, as opposed to 750 cm that would be seen by the sensor if it interrogated an unenclosed cloud, the detected laser power is equivalent to that of an unenclosed cloud with 0.4 – 4 g/cm^3 mass density.

The dust cloud was illuminated with ~ 10 mW of laser power, modulated sinusoidally at 10 kHz with 25% modulation depth. Lock-in detection measured the amplitude of the modulated backscattered light with 10 Hz bandwidth. Figure 14 plots the detected signal during the transient cloud event for cloud densities of 80, 40, 17, and 8 g/m^3. In each case, the dust was introduced at t = 150sec and the cloud disappeared (particles settled) within a minute. There was a baseline signal due to scattering from chamber windows that was very sensitive to slight movements of the transceiver or chamber.

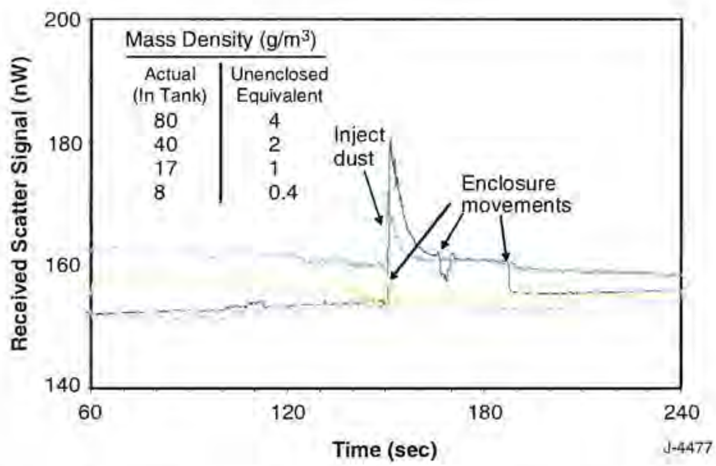

Figure 14: Temporal records of scattered light power received by the particle sensor.

Figure 15 compares the scattering signal measured in these experiments with the values shown in Figure 15 for 20 μm particles. ***The remarkably good comparison verifies that the backscatter technique will be suitable for standoff detection of particle clouds that are potentially explosive or immediately hazardous to breathe***.

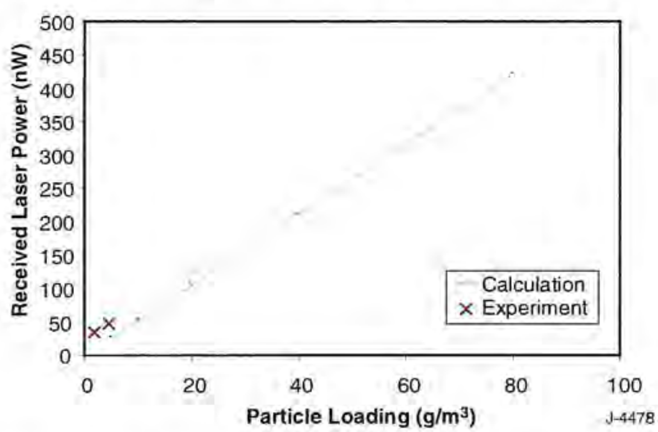

Figure 15: 5m standoff conceptual scatter sensor signal versus coal dust aerosol mass density. Laser source is 1600 nm and 10 mW.

6. Conclusion

This Phase I SBIR developed technology that enables portable lightweight standoff detection of multiple hazardous gases and explosible particulates. Its intended use is by miners to enhance their safety by enabling detection of explosion hazards remotely and prior to entering a hazardous area.

Phase I demonstrated the feasibility of building compact laser-based instruments that continuously and remotely probe the environment for multiple hazards and provide early warning of immediately dangerous conditions prior to miners entering a hazardous area. Phase I also taught that there are additional miner safety applications of the sensing technology. These include monitoring for explosive gas accumulations within sealed and other inaccessible mine areas, inspecting new mine face walls for methane sources, as well as monitoring for toxic gases in active mine regions. Current techniques, using Combustible Gas Indicators for example, require use of a probe that physically enters the area of interest and withdraws a gas sample through a hose that dilutes the sample and delays the analysis. The laser-based standoff sensors demonstrated in this project require only that a laser beam illuminate the sampling area. They rapidly readily scan wide areas and provide instant analysis, thereby offering the opportunity to simplify mining procedures while enhancing miner safety.

30 CFR 75.351 specifies means and locations for installing and operating CH_4, CO, and smoke sensors in coal mines. While not specifically excluded, current regulations do not readily embrace standoff sensing of explosion hazards. Therefore, though it is a technology that potentially offers significant health and safety benefits, to gain acceptance by the mining industry the PSI multi-hazard sensor suite needs to be developed, proven, and written into regulations.

This work revealed that the multi-hazard sensor platform offers capability to address several mine safety applications, each requiring a unique optical configuration and method of use. Thus, a principal outcome of Phase I is the recommendation that, rather than focus on the helmet-mounted configuration addressed in Phase I, the Phase II project should emphasize development and demonstration of a configurable technology platform.

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8. Publications

None