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Real-Time Monitoring of Total Inward Leakage of Respiratory Equipment Used by Emergency Responders: Workshop Proceedings

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NIST National Institute of Standards and Technology • U.S. Department of Commerce

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ABSTRACT

A workshop on respirator sensors was held at the National Institute of Standards and Technology (NIST) on May 1, 2009. The objective of this workshop was to discuss and document the need for real-time monitoring of the respiratory intake of emergency responders; to identify appropriate sensing technologies; and to identify and discuss a scientific strategy (employing both modeling and experimental validation) to determine optimal implementation of respirator sensors. This workshop was attended by over 25 people from the fire service, industry, government agencies, and academia. Collectively, they had expertise in the areas of chemical detection, occupational health and safety, firefighting technology, fluid flow, and fire protection engineering. Speakers gave eleven presentations in three sections that identified the needs of firefighters, reviewed the state of sensor technology, and stated the challenges posed by the integration of this technology into SCBA respirators. At the conclusion of each of these sections, the participants discussed ideas, issues, and concerns with real-time monitoring. This report summarizes the knowledge gained from this workshop and our analysis of the scientific and engineering challenges involved in the development and implementation of respirator sensors.

The report is structured by the three sections of the workshop: First Responder Needs and Concerns, Sensor Technologies, and Sensor Integration and Engineering. In each section, descriptions of each talk are followed by the points covered in the discussion among workshop attendees. The presentations themselves are provided in the appendices.

ACKNOWLEDGMENTS

The success of any workshop is dependent on the hard work of the individual speakers, facilitators, and participants. These proceedings are an assimilation of the contributions from everyone involved in the workshop; copies of the presentations are included in the appendices. Thanks to all who made presentations and to those who participated in the workshop.

We appreciate the assistance of Ms. Barbara Huff of NIST, who helped with travel and other logistics. Thanks also go to Teresa Vicente, who set up the online workshop registration.

The Science and Technology Directorate of the U.S. Department of Homeland Security funded the production of the work presented in this material under Interagency Agreement HSHQDC-08-C-00406 with the National Institute of Standards and Technology (NIST). The results published herein are solely the responsibility of the authors.

1 INTRODUCTION

The atmosphere within a burning building is deficient in oxygen but rich in carbon dioxide, soot, and other aerosol particulates. Dangerous levels of carbon monoxide are almost always present in fire effluent, which can also contain hydrogen cyanide, hydrochloric acid, and known carcinogens including benzene, formaldehyde, and polyaromatic hydrocarbons.

Firefighters and other emergency responders depend on respiratory protective equipment to protect them from these hazardous substances while they are working in fire environments and under other IDLH (immediately dangerous to life and health) conditions. A self-contained breathing apparatus (SCBA) is typically used, consisting of a full-facepiece respirator mask covering mouth, nose, and eyes, an air cylinder, and a pressure regulator (Figure 1). The SCBA is operated under positive pressure, so that in the case of a leak, the flow of gases is designed to be outward. However, momentary negative pressure conditions have been recorded in testing, and it is uncertain whether there are conditions under which a leak in the seals or exhalation valve may allow harmful substances to get inside of the mask.

Figure 1. Firefighter gear including SCBA.

The breathing gases are supplied by a cylinder carried by the user. In the US, the majority of fire companies use compressed air, which is inexpensive and easy to supply using compression equipment at the firehouse or close to the fireground. A disadvantage is the limitation of respirator usage time for a single air cylinder to an hour or less, depending on bottle size and fill pressure, which can be reduced to as little as 10 minutes for exceptionally high workrates. The quality of the compressed air depends on the quality of the supply, and care must be taken to place the pump input away from fire equipment engine exhaust and other sources of pollutants. Breathing gas cylinders for firefighters may alternatively contain air liquified using liquid nitrogen or compressed oxygen. The latter is the closed-circuit SCBA, which both employs a CO_2 scrubber to maintain a breathable environment within the respirator and supplements the depleted oxygen with addition of O_2 from a cylinder. Both liquid air and compressed oxygen technologies provide significantly longer respirator usage times, with the disadvantages of higher complexity and expense. However, regardless of the type of system, for the positive pressure SCBA respirator a leak will increase the rate at which breathing gases are used.

Prior to certification to use a SCBA, each firefighter must pass a fit test to demonstrate that the selected facepiece fits sufficiently well. In the past, this fit test asked firefighters to report the detection of odors when immersed in an environment containing a test gas, such as banana oil. Most fire companies now use the Porta-Count, a device that compares the number of particles detected outside the respirator mask with those detected within, under conditions that include various head and body movements and talking. The degree of protection provided by the respirators is quantified by several measures, including the fit factor (FF) measured during the fit test, the assigned protection factor (APF) that the respirator is expected to meet, and the workplace protection factor (WPF) that is actually experienced in the workplace.[1] Ideally, the concentration of each type of hazardous gas or particulate within the respirator would be measured in real time and an alarm would signal values that exceed the permissible exposure limit. This is not currently practical, however, due to the complexity of the hazardous environment and limitations in commercial sensor technology. The environment faced by the firefighter is not well-characterized. In addition, synergistic effects that may worsen the health effects of one component in the presence of another are not well-known.

To maintain their certification to use their SCBA, firefighters must pass fit tests every year. This regimen is intended to ensure that the user is not exposed to hazardous substances while using their SCBA in fire environments. However, little data exists to support this assertion and there are some reasons to question it, as will be discussed later in this report. If, however, conditions inside the SCBA mask were monitored in real time, the user could be alerted in the event that the equipment fails to provide adequate protection due to inward leakage from poor face fit or a mechanical failure, such as a leak in the exhalation valve.

Monitoring the respiratory intake of a firefighter using a SCBA is a challenging problem. The sensing technology to do this must be adaptable to the constraints imposed by facemasks in geometry and in power availability (e.g. battery life requirements) and at the same time must be responsive, sensitive, and sufficiently robust to survive and perform in a fire environment. Furthermore, respirator sensors must be positioned so that the readings accurately reflect respiratory intake. Placement of sensors at the intake through the mouth or nose may be representative, but this may not be practical, and locating sensors within dead spaces and eddies will adversely affect their response.

A workshop on respirator sensors was held at the National Institute of Standards and Technology (NIST) on May 1, 2009. The objective of this workshop was to discuss and document the need for real-time monitoring of the respiratory intake of emergency responders; to identify appropriate sensing technologies; and to identify and discuss the development of a scientific strategy (employing both modeling and experimental validation) to determine optimal implementation of respirator sensors. This workshop was attended by over 25 people from the fire service, industry, government agencies, and academia. Collectively, they had expertise in the areas of chemical detection, occupational health and safety, firefighting technology, fluid flow, and fire protection engineering. Speakers gave a total of eleven presentations in three sections that identified the needs of firefighters, reviewed the state of sensor technology, and stated the challenges posed by the integration of this technology into SCBA respirators. At the conclusion of each of these sections, the participants discussed ideas, issues, and concerns with real-time monitoring. What follows is a report of what was learned from this workshop and our analysis of the scientific and engineering challenges involved in the development and implementation of respirator sensors.

The report is structured by the three sections of the workshop: First Responder Needs and Concerns, Sensor Technologies, and Sensor Integration and Engineering. In each section, descriptions of each talk are followed by the points covered in the discussion among workshop attendees. The presentations themselves are provided in the appendices.

2 FIRST RESPONDER NEEDS AND CONCERNS

Presentations on issues associated with respirator fitting and the use of SCBAs by firefighters were given by Ziqing Zhuang, a research engineer at the National Personal Protective Technology Laboratory (NPPTL) of the National Institute for Occupational Safety and Health (NIOSH), and Dawn Bolstad-Johnson, an industrial hygienist with the Phoenix Fire Department.

2.1 NIOSH Fit Test Research – Ziqing Zhuang (NIOSH / NPPTL)

To ensure safe use of any respirator with a tight-fitting facepiece, first responders must pass a fit test. For SCBAs, this must be a Quantitative Fit Test (QNFT), in which the concentrations of a surrogate substance are measured in the surrounding atmosphere and within the respirator mask. The widely-used Portacount instrument, for example, counts the number of particles inside and outside the mask. The fit test is typically mandated prior to the initial use of the respirator, at least annually thereafter, and also whenever there is a change in the respirator facepiece or in the physical condition of the wearer. The ratio of the concentration outside to the concentration inside the facepiece, referred to as the fit factor (FF), is a measure of how effective the mask is in preventing inward leakage of gases and particulates. For the purposes of the fit test, the SCBA air tank is disconnected and HEPA filters are attached to the facepiece so that the respirator is functioning in negative pressure mode. To pass, the overall FF must exceed 500. This corresponds to an assigned protection factor (APF), the level that must be met in the workplace by the respirator, of about 10,000 under normal operating conditions in which the pressure is positive.

The fit test is an art as well as a science. In the attempt to predict workplace protection from a test performed in a relatively clean room under controlled circumstances, the test must incorporate a large margin of safety. The overall FF is calculated over several exercises, including bending, turning side to side, turning head up and down, and talking. During the exercises, a leak in the chin region is sometimes observed. Talking may result in additional particles in the mask emitted by the lungs, confounding Portacount measurements that compare the number of particles inside the mask to outside. Two types of error are identified for fit factors: the alpha error, which describes the error that the wearer fails the fit test while the respirator adequately fits the wearer, and the beta error, which describes the error that allows a respirator to pass the fit test even though it doesn't fit very well.

Given these issues, validating fit test methods is an important focus of recent NIOSH/NPPTL research efforts. A fit testing milestone is shown in Figure 2, in which a correlation was demonstrated between FF and actual exposure (measured by analyzing end-exhaled air for Freon-113 concentration) experienced by the user of half-mask respirators.[2] Recent research efforts also found correlation between quantitative fit test results with actual workplace protection for half-facepiece respirators.[3]

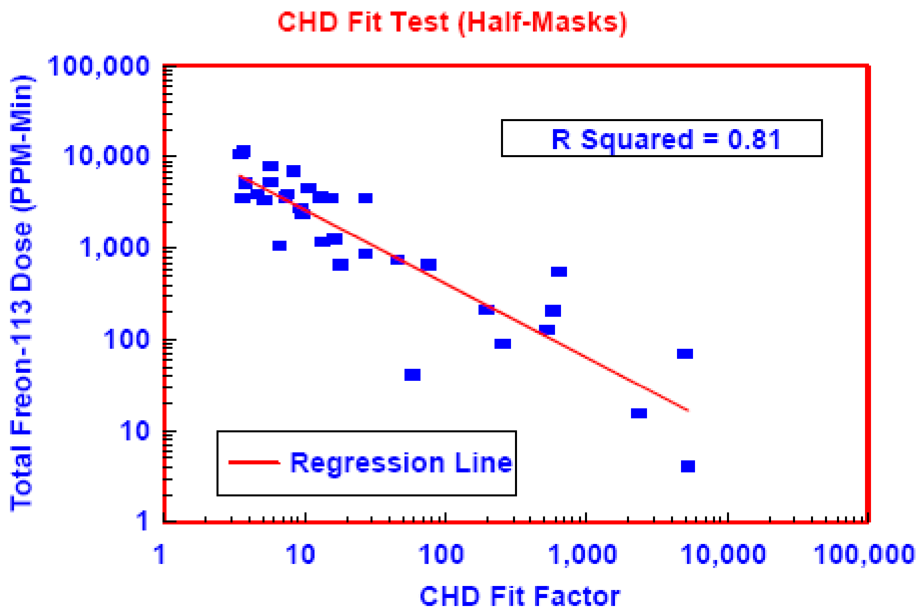


Figure 2. Correlation between fit factor and actual exposure for Continuous High Flow Deep Probe fit test.

Current respirator fit research at NIOSH includes the characterization of worker faces through anthropometry, the investigation of the correlation of facial dimensions with fit, and the definition of new fit test procedures, such as multiple donnings and variations in exercise type and duration.[4,5] The goal is to reduce both alpha and beta errors. One approach is to determine which fit test exercises (talking? nodding?) contribute most to the variability of results. The measurement of FF in the workplace continues to be a challenge. Possible sensor measurements to monitor FF include pressure drop, ambient particles, and CO_2 (exhalation vs. inhalation). In addition, there is the question of whether the Portacount instrument could be made transportable. A potential remote measurement is surface temperature measured with an infrared (IR) camera, which is currently being used to look for flu victims.

2.2 Fit Testing First Responders – Dawn Bolstad-Johnson (Phoenix Fire Department)

The Fire Department in Phoenix, Arizona dispatches approximately 145,000 emergency calls each year. Of these, about 10 % (14,500) are fires, and about 1000 are large fires. This represents a significant base of experience among the 57 fire stations and 1677 members servicing this community.

Phoenix firefighters are fit-tested at least annually, using the OHD Portacount and the six-step REDON fit test protocol.[6] In order to pass the fit test, firefighters may cinch the respirator more tightly than they would at the fire, sometimes resulting in red marks on the face.

Facial features are observed to affect the fit test results. Temples are a problem area, and narrow faces, high cheekbones, long chins, and facial scarring can cause difficulties. The

82 female members are overrepresented among those difficult to fit. In 2009, 10 individuals out of about 1700 failed their fit tests and were refitted with new respirator masks. The number represents a significant improvement over the previous year and parallels a change in respirator supplier. For one firefighter, a fit was achieved by attaching foam to the seal.

Fit may change with time between fit tests. The shape of the face may change, due to dental work and weight gain or loss, for example. The respirator seal may also change. Seals may become distorted during improper storage in areas that are not environmentally controlled, such as those shown in Figure 3. Changes in temperature (e.g. for respirators left in the trunk of a car) affect the elasticity of the seals and straps that secure the mask to the face.

Figure 3. Some storage conditions for respirator gear.

The evidence for respirator leaks leading to inhalation of smoke during fire operations is not well characterized. Some firefighters have reported experiencing a condition referred to as "blow-by" – soot marks on the face or in nose mucus – that suggest that soot has penetrated the facemask during the fire. However, it has not been possible to reproduce this phenomenon under controlled circumstances, and the obvious conclusion that it is due to a leak is confounded by the practices of clicking the regulator into place only when smoke is smelled and of removing the SCBA during overhaul. In addition, masks are currently stored in black cases that go into the fire area and get dirty themselves. On the other hand, it is not uncommon for firefighters to bump into things while they are working to put out a fire, which can disturb the position of the facemask enough to cause a temporary negative pressure and perhaps a transient leak. In addition, heavy sweating and hard breathing can adversely affect the fit of the mask to the face and cause the internal pressure to become less than ambient.

The idea of real-time monitoring of respiratory phenomena during fire operations raises some questions. What should be the response of the firefighter or incident commander to a temporary negative pressure that is then fixed, such as that caused by a bumped mask? A slow leak in a positive pressure respirator system means that the bottle makes up the difference, resulting in less time until the air runs out. Since small leaks around the face would cause the air cylinder to dump more air, should the additional flow of air be monitored and reported?

2.3 Discussion

The discussion period following this set of talks addressed the nature of leaks for an SCBA, the blow-by phenomenon, possible applications for sensors, and concerns about real-time monitoring.

An SCBA is a positive pressure device, so that the natural direction of flow in the presence of a leak is outward. The demand valve responds to any lowering of pressure with increasing release of supply air. However, certification requires pressure testing on a breathing machine only up to a maximum demand of 300 L/min. Since peak respiratory flow rates can exceed this value (probably reaching values as high as 450 L/min to 470 L/min, although up to 700 L/min is claimed by some), it is possible that the pressure inside of an SCBA may become negative at times when the firefighter is breathing heavily due to extreme exertion. This is referred to as overbreathing the respirator. Furthermore, it is known that there are spatial variations in the pressure due to the complexity of the flow fields created by the interaction between the stream of air coming from the cylinder and respiration within the confines of the facemask. Thus, to the extent that there are times when the pressure falls below ambient in any region of the facemask, the user will be vulnerable to inward leakage of hazardous gases and particulates. Leaks are possible through the face seal and valves. For filtering facepiece respirators, leaks are also possible through the filter cartridge.

Physical evidence that suggests respirator leaks may be occurring during a fire includes the facial markings and black nose mucus known as blow-by. Outward streaks appear to represent a positive pressure leak combined with sweating. Streaks along the cheekbone have been reported but not confirmed. Blow-by has been observed in Phoenix and by firefighters in other locations as well. Claire Austin, a Canadian researcher, noted that this is a historical problem that she has not been able to replicate. She hypothesized that it may have been due to dirty equipment, such as from oil getting into the cylinder. In real situations, the user can usually feel a leak. It was speculated that there should not be blow-by unless the firefighter takes off the mask early, and that the soot may be transmitted to the face by touching. Workshop participants agreed that this phenomenon requires further study.

A side issue of safety was brought up regarding body smells that may last up to three days after a fire. Personal protective clothing worn by firefighters doesn't seal against gases, which may be absorbed by the skin and hair. Some female firefighters have asked if it is safe to breastfeed after having participated in a major fire. The risks of these absorbed gases and the outgassing odors are unknown.

There was much discussion about the best use of sensors. While a smart mask that monitors its own fit and protective capability can be a goal for the future, there are other applications worth consideration. Some participants, especially representatives of the fire services who have direct experience with the use of SCBAs and other firefighting technologies, supported the idea that portable sensing devices could be used to determine when it was safe for firefighters to disconnect their air cylinders and remove their facemasks. A scientific measure of hazardous substances could help to break down some of the cultural resistance to wearing a respirator during overhaul, for example. Sensors could collect data on respiratory protection in the workplace, answering the question of what gases and particulates get through the protective barrier of the respirator, and the results can be compared with controlled laboratory experiments. Sensors can also be used to collect data on metabolic effects and to monitor health. How the conditions in the respirator affect health remains an unanswered question. In addition to providing valuable information, data collection may be a useful way to introduce sensor technology into the firefighting culture. As with any new technology, acceptance requires a long time, and the wearer needs to be able to trust the sensor if he or she is to make decisions based on its output.

Several concerns were raised about the capabilities and appropriate usage of respirator sensors. The first question is what should be measured. Particulates are different than vapors. Diffusion coefficients differ, as do filtration and permeation characteristics. Health effects for particulates are strongly dependent on size, and there is a wide range of sizes of particles generated in a fire. Standard fit tests are not necessarily a good guide for sensor choice. Corn oil vapor, sometimes used in fit tests, is not the same as the materials in the fire. The Portacount fit test is based on particulates, although it is at least as important to protect the first responder against gases. The chemical species of gas to measure is not clear. For example, carbon monoxide is not a good surrogate for other fire gases. It may be most appropriate to use multiple sensors to monitor multiple gases. Other issues include how to determine whether the sensor is sensitive enough and fast enough for the purpose of monitoring protection, and how much information to provide the wearer. Some wearers find the heads-up display in some new respirators to provide too much data and turn it off.

3 SENSOR TECHNOLOGIES

The modification of SCBA facemasks to include sensors capable of detecting hazardous gases or unusual pressure changes, and thus detecting leaks and monitoring the fit factor, would provide assurance that a SCBA is working properly and that the user is protected. Although this is a challenging technical problem, recent advances in microelectronics have enabled the development of a new generation of novel, compact sensors that appear to possess many of the properties required for this application. The current state of the art in sensor technology was reviewed in a series of presentations by Brian King, a Ph.D. student at the University of California at San Diego (UCSD), Kurt Benkstein, a research chemist working in the Chemical Science and Technology Laboratory (CSTL) at NIST, Nathan Lazarus, a Ph.D. student at Carnegie Mellon University (CMU), William King at NIOSH/NPPTL, and Gary Hunter, a researcher at the National Aeronautics and Space Administration (NASA).

3.1 Gas Sensing with Porous Silicon Photonic Crystals – Brian King (University of California at San Diego)

Professor Michael Sailor and co-workers at UCSD are working with NIOSH/NPPTL on the development of microsensors for the detection of organic vapors as they break through a filter bed, signaling the end of life for a respirator filter. These devices must be small, sensitive, and tunable to the type of gas whose passage the filter is designed to prevent. To accomplish this, these investigators have fabricated thin films made from porous silicon crystals.[7] Electrochemical etching generates rugate pores, characterized by wrinkles whose periodic structure determines the refractive index of the crystalline film.[8] The structure is well-controlled and is designed to correspond with the gas to be detected. When irradiated with white light, the crystals reflect only light within a narrow band of a specific wavelength determined by the refractive index. If the air that occupies these pores is displaced through capillary condensation by an organic compound, it results in a characteristic spectral shift that can be measured. An example from the presentation shows air reflecting as green while toluene vapor reflects as orange.

Figure 4 shows how this sensor is used to signal breakthrough of organic vapors in a filter. The sensor is mounted at the tip of an optical fiber probe that is embedded into the filter at the desired monitoring position. The probe is attached to both a light source and to a spectrometer that detects a shift in reflected wavelength. The magnitude of the spectral shift indicates the type of vapor detected and the concentration, and the specificity can be improved by modifying the surface chemistry of the film. Sensor response time is on the order of 10 s. The researchers are also looking into ways to decrease the power requirements of the light source and the detection circuitry with an LED and photodiode detection system.

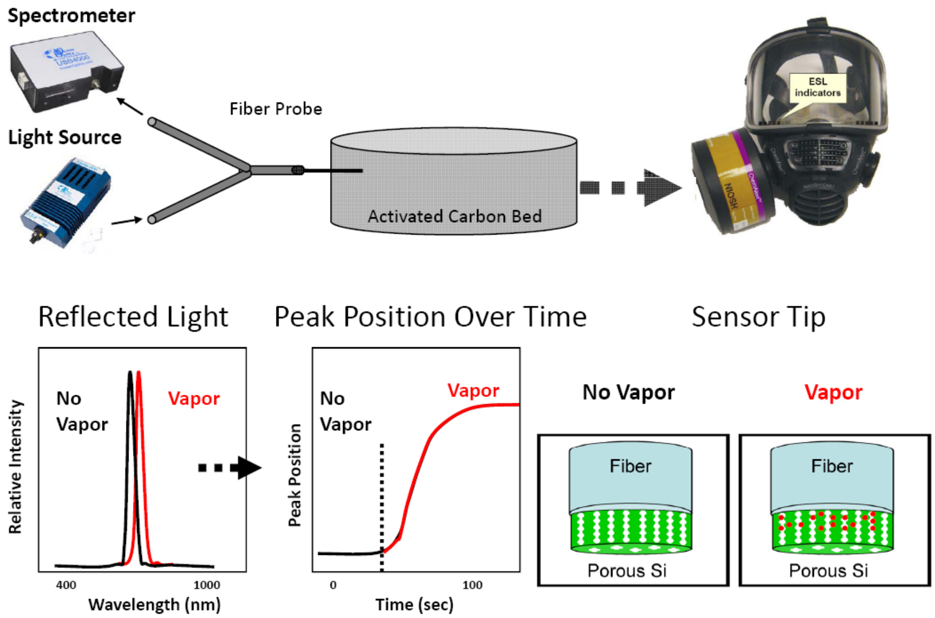


Figure 4. Spectral shift caused by displacement of air by organic compound.

The characteristics and advantages of this approach are:

- Flexible, thin fiber optic sensors for gases and vapors
- Simple fabrication
- High sensitivity to small quantities of a gas due to the large surface area
- Good selectivity due to easy modification of the surface and tunable optics – allows targeting of classes of vapors
- A multiple sensor array may be used to detect multiple vapors
- Size – miniaturization of fiber optic sensors and source/detection hardware
- Low power

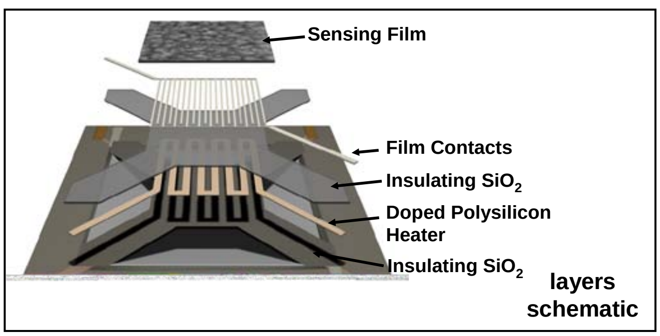
Some issues are:

- How long is the response time? The response depends upon the diffusion rate of the gas into the porous film and ranges from milliseconds to minutes depending on the physical properties and concentration of the gas and the thickness, surface chemistry, and morphology of the sensor film.
- What happens if the device sits in diesel fumes for a while? The device can be reset with heat at a temperature over 100 °C.
- The system must be calibrated with temperature.

3.2 NIST Chemiresistive Microarray Technology – Kurt Benkstein (NIST/CSTL)

Scientists in the Chemical Science and Technology Laboratory (CSTL) at NIST are working on another sensor technology that has potential for application to respirators. Dr. Steven Semancik and co-workers have pioneered the development of microhotplate arrays with metal oxide sensing films, with the objective of developing tunable chemical/biochemical microsensors that are reliable even in complex dynamic environments.[9] The microhotplate is a matrix of sensing elements, each of which is approximately 100 μm x 100 μm in size. As shown in Figure 5, each element consists of three functional components: a polysilicon resistor, which generates heat by application of a current, platinum interdigitated electrical contacts, and a metal oxide sensing film. An insulating layer of silicon dioxide (SiO_2) separates the functional regions. The adsorption of gaseous agents onto the metal oxide film changes the electrical conductance of the film. A combination of sensing materials and temperatures results in a characteristic electrical signature that is different for each gas. Due to their extremely low mass (~0.2 μg), these assemblies can be temperature-ramped very rapidly to about 500 ºC, with heating rates approaching 10^6 ºC/s. This ability to program the temperature of the sensor in time, and thereby to change the kinetics of the chemisorption process, provides an additional dimension for distinguishing between analytes. It is straightforward to replicate this structure to produce multi-element arrays, as shown in the bottom of Figure 5. Signal processing methods train the device to discriminate between multiple target chemicals in real time.

In his presentation, Dr. Benkstein presented data demonstrating the use of microhotplates with metal oxide sensing films to detect dangerous industrial chemicals, such as ammonia and hydrogen cyanide, in an environment containing non-targeted chemicals such as paint fumes and window cleaner and further complicated by humidity. These results are particularly promising, since many of these gases are known to be present in fire atmospheres. Current work on the monitoring of exhaled breath for the presence of acetone, a biomarker for diabetes, is directly applicable to the respirator application of interest at this workshop.



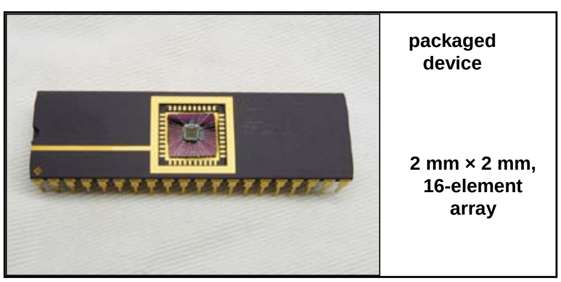


Figure 5. An insulating layer of SiO2 separates functional regions.

The advantages of this approach are:

- Miniaturization on a chip
- Ease of expansion – A single chip can house a matrix of sensors to separate several specific chemicals
- Use of signal processing to train the device to recognize and classify chemicals
- Monitoring of breathing is currently being studied

Some issues are:

- Higher sensitivity to trace concentrations of µmol/mol and below, shorter response time, and longer stability to drift, which may be improved by the use of nanostructured materials
- Training the device to ignore dynamic changes in the background environment, such as fluctuating humidity and innocuous species (interferents)
- Dealing with temperature cycling, which changes the conductivity and shape of the response. This requires good understanding of the effects of heating within the respirator facepiece

3.3 MEMS Sensor Development for End-of-Service-Life Indicators – Nathan Lazarus (Carnegie Mellon University)

A research effort directed by Professor Gary Fedder at CMU, in collaboration with NIOSH/NPPTL, has demonstrated the efficacy of gold nanoparticle chemiresistor sensors as End-of-Service-Life Indicators (ESLIs) for respirator filter cartridges.[10] This application uses MEMS (microelectromechanical systems) technology to integrate an array of sensors, potentially including chemiresistors, mass-sensitive cantilevers, and humidity and temperature sensors, with signal processing electronics to create an "electric nose". MEMS technology is currently used in automobile airbag accelerometers.

To create a chemiresistor sensor, gold nanoparticles dissolved in trichlorobenzene are deposited by an ink jet printer onto a spiral gold electrode etched on a silicon substrate. The sensor has a diameter of about 200 µm. As shown in Figure 6, the presence of volatile organic compounds can be detected by monitoring the resistance of the electrode, since chemisorption increases the distance between the gold nanoparticles. A second method measures chemisorption by monitoring changes to the frequency of a cantilever gravimetric sensor, as shown in Figure 7.[11] These sensors are sensitive enough to measure very small concentrations in the nmol/mol range. They can be reset by heating. In addition to the chemical sensors, sensors for humidity and temperature can be fabricated to measure changes in dielectric capacitance and metal resistance respectively.

The complete MEMS device may consist of an array of sensors to measure chemicals of interest, temperature and humidity. The integrated electronics analyzes the sensor data, using the temperature and humidity sensors to compensate for these factors. The device is then embedded into the respirator filter cartridge at a distance from one end that provides for adequate warning of impending chemical breakthrough.

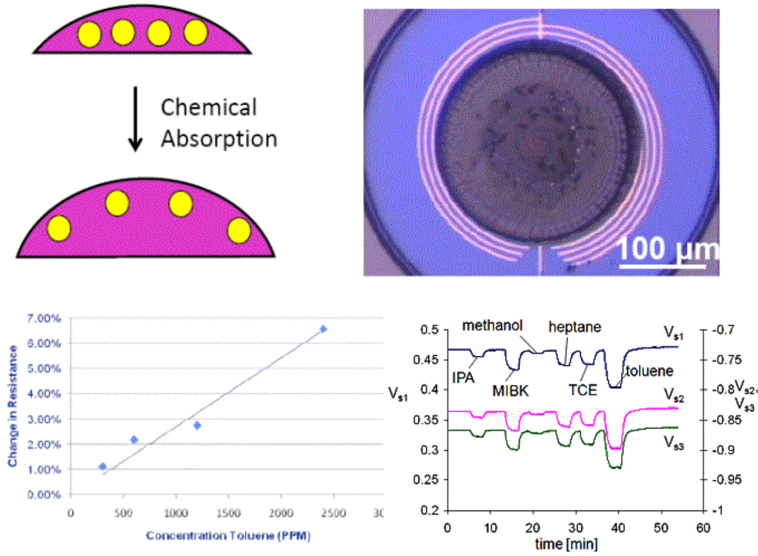
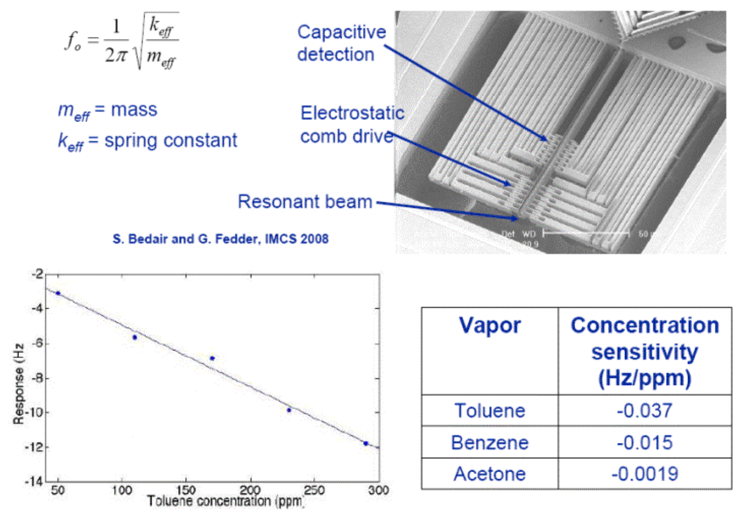


Figure 6. Chemiresistor sensor, in which changes in electrical resistance indicate the presence of volatile organic compounds.[10]



Vapor	Concentration sensitivity (Hz/ppm)
Toluene	-0.037
Benzene	-0.015
Acetone	-0.0019

Figure 7. Cantilever sensor, in which changes in resonant frequency indicate the presence of volatile organic compounds.[11]

The advantages of this approach are:

- Size – Miniaturized mechanical structures, integrated electronics for signal processing
- Sensitive to a range of chemicals in the pmol/mol range
- Ease of expansion – Array of sensors
- Stable – long shelf life, insensitive to temperature and humidity
- Low cost

Some issues are:

- The presence of particulates, which may interfere with the mechanical cantilevers
- Handling the temperature variations resulting from heating within the respirator facepiece

3.4 Ultrasound in Respirators: Concepts and Preliminary Results – William King (NIOSH/NPPTL)

Dr. William King from NPPTL/NIOSH reported on preliminary results for a different approach for monitoring inward leakage in respirators. Rather than sensing the presence of an unwanted compound, this work seeks to detect the leak by measuring ultrasonic acoustic emissions associated with the flow field in the mask. The work was motivated by the much lower value and large scatter in measurements of Workplace Protection Factors (WPF) compared to Quantitative Fit Factors (QNFF). To identify the most important factors that account for this difference in WPF, there needs to be a method to monitor fit factor of the actual respirator in real time during workplace operations.

Ultrasound is a frequency range of sound pressure that is outside of the human audible range and is not identified with a health risk. It can be used to detect a leak in one of two ways. An ultrasound generator on one side of the leak may send out a signal that is detected and analyzed by a receiver on the other side, or, if the flow through the leak is turbulent, the leak itself may generate detectable ultrasound radiation. Estimates of the flow through a presumed respirator leak and from ordinary respiration show that only nasal breathing is expected to be a source of ultrasound. Initial investigations show that the strength of the ultrasonic signal through a leak from either a controlled source or from nasal breathing provides a measure of the leak size. As shown in Figure 8, a correlation was found between acoustic intensity and protection factor measured in a traditional manner for several half-facepiece respirators, indicating that this approach may be feasible. The timescale for leak detection is on the order of seconds.

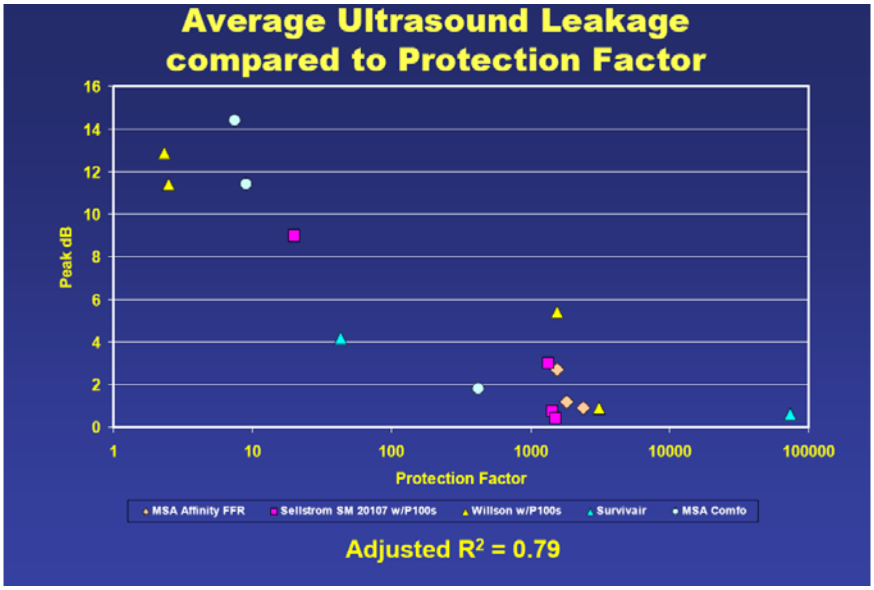


Figure 8. Correlation between acoustic intensity and fit factor.

The advantages of this approach are:

- Small size
- Low power
- Low cost
- Uses well-developed acoustic technology
- Highly insensitive to temperature and humidity

Some issues are:

- Where should the ultrasound sensor be located? How many? For example, would five sensors around the seal be sufficient to detect all seal leaks?

3.5 Chemical Sensors for Aerospace Applications: From Sensor Platforms to System Application – Gary Hunter (NASA Glenn Research Center)

Scientists and engineers in the Instrumentation and Controls Division at the NASA Glenn Research Center have designed many microsensors packaged in chips and integrated into printed circuit boards for aerospace applications including detecting fuel tank leaks, dangerous emissions, and fires. At the workshop, Dr. Gary Hunter presented a range of gas sensor technologies that have broad potential use. Some versatile, user-friendly, and durable microsensors that have been tested and deployed by NASA in recent years are illustrated in Figure 9.

The approach taken at NASA is to develop an intelligent system by distributing capabilities to smart components at the local level.[12] Important principles include "Lick and Stick" stand-alone stamp-size technologies using micro and nano fabrication techniques to place tiny sensors, actuators, electronics, battery power, and (wireless) communication where needed, reliability, redundancy and cross-correlation of data to improve trust, and orthogonality to increase the range of system information. Existing gas sensors based on MEMS technology can measure hydrogen, oxygen, CO, CO_2, NO_x, and hydrocarbons, and some sensor platforms have built-in temperature, pressure, and/or humidity detectors and heaters. The microfabrication technology permits tailoring of the specific sensor array to the application. Attention is given to supporting technologies, such as packaging, which can be as much as 70 % of the device cost, signal conditioning and processing, software for neural nets or modeling, and power and communication networks.

Applications for NASA's chemical sensors that relate to this workshop include fuel and oxygen leak detection on spacecraft, detection of fire and fire precursors, detection of toxic gases, combustion control, and breath monitoring for human health. Detection may take place under harsh temperature conditions or in the presence of interfering gases. False alarms are reduced through orthogonal detection and cross-correlation of sensor data. Testing is rigorous. The FAA "biscuit", which burns in a repeatable manner and releases the same gases each time, may be used. The sensor system must be able to continue operating through repeated cycles in harsh environments.

NASA's vision of a "smart" suit that monitors both internal and external conditions to maintain the health of the wearer and the integrity of the suit can be a model for the first responder as well. Breathing gases that can be used to monitor human health include water vapor, CO_2, O_2, NO, CO, volatiles (VOC) excreted during exhalation, and semivolatiles in breath condensate. Known biomarkers for various diseases can be tracked. NASA has demonstrated the capabilities of a prototype breath analysis system, although it is not unobtrusive as would be needed for first responder use. This system is on a path to eventual commercialization through the State of Ohio Third Frontier Program.

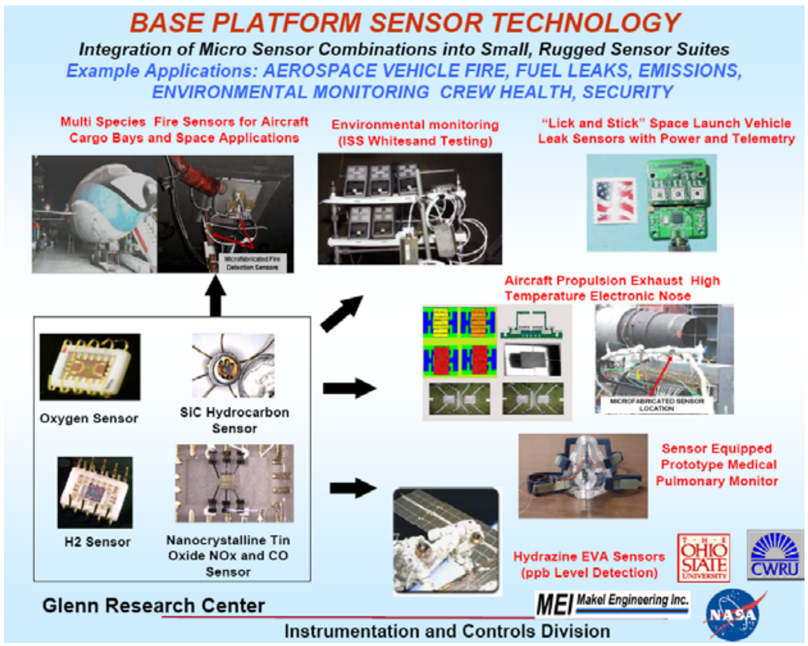


Figure 9. Examples of gas microsensors that have been tested and deployed by NASA in a variety of applications.

The advantages of this approach are:

- Small size – miniaturized sensors and electronics
- Response time, sensitivity, selectivity, stability
- Batch fabrication, processing reproducibility, control of structure
- Sensor system tailored for the application
- Low power
- Minimum size, reduced weight, and reduced power consumption are important goals
- Consideration for harsh environments, including high temperatures and particulates

Some issues and lessons learned are:

- Customer acceptance, ability to trust the data, requires working closely with the customer

- Need for sensor arrays to carry out multiple measurements at once
- Importance of supporting technologies such as packaging and software
- Breath to breath resolution
- Nanotechnology fabrication challenges

3.6 Discussion

At the conclusion of this set of talks, the workshop participants raised a number of issues relating to sensor technology. Of particular concern were the specific quantities that should be monitored, the confounding effects of heat, humidity, and particulates, where the sensor should be located, and what kind of information is important for the wearer to know.

There was no consensus on what gaseous compounds should be targeted, or whether it would be sufficient simply to detect the presence of a leak using pressure or acoustic sensors. Carbon monoxide is a gas that is found in all fires in which incomplete combustion takes place; however, it cannot be considered a tracer gas. In other words, monitoring CO alone may not give sufficient information about the hazards to which the firefighter is exposed. Other gases that are often encountered in a fire include hydrogen cyanide (HCN), nitrogen oxides (NO_x), sulfur dioxide (SO_2), hydrogen chloride (HCl), and various hydrocarbons. In addition to the most toxic gases, it was suggested that it would be a good idea to also target agents such as benzene and formaldehyde that have been identified as contributors to chronic diseases suffered by firefighters. Additional concerns could be addressed by a sensor for CO_2 to monitor CO_2 build-up in the respirator and a sensor for oxygen to identify low oxygen conditions. Multi-sensor arrays would certainly provide more information on the contents of the "soup" of the fire environment, although there is a need for further study on what materials to include and exclude from the sensor array.

It was noted that the hot, smoky, high thermal flux conditions that prevail in a fire are extremely demanding and would likely degrade the performance of the sensors, possibly even damaging them. A particularly challenging test of sensor robustness used by NASA is the so-called "Disk of Death", a polymer-based fuel that produces a nasty soup of chemicals when ignited, often overwhelming the sensor. The presence of heat, water, and particulates were cited as major problems that might confound the sensor or saturate it and make it insensitive to more hazardous compounds. The incorporation of humidity and temperature sensors would be one approach for compensating for this problem. A multiparameter, multisensor approach would be more able to characterize the environment from the measurements.

Particulates can interfere with sensors by contaminating surfaces. For a mechanical sensor such as the cantilever discussed in Nathan Lazarus' presentation, particulates could prevent its operation. In the smoky environment of a fire, this is a major problem that suggests the importance of proper sensor mounting and packaging, potentially necessitating a filter. Small particulates are also a health hazard, however, and may warrant a sensor of their own.

Workshop participants again discussed where the sensors would be located. One suggestion was to put sensors in the turnout coat, for the purpose of measuring gases that may be absorbed into the skin. A sensor measuring the external environment could provide data to guide the decision on when the firefighter can remove the respirator. This capability would require setting criteria for respirator removal, which in turn requires further research into health effects, followed by practical methods for enforcing new procedures. Measurements both inside and outside the respirator would provide the best record of what the hazard is and how well the firefighter is protected against it. The sense of the workshop was that there are a lot of opportunities here – to determine when it is safe enough to remove the respirator, to monitor breathing uptake of hazardous gases, to track the physiology of the firefighter including heat stress, and to monitor the condition of the PPE itself.

Finally, the participants discussed how the information from the sensors should be conveyed to the user of the SCBA. A sensor can provide too much information. To be useful, it needs to call attention to itself only when the value changes in an important way. In order to avoid overload, the firefighter on the scene wants it kept very simple, on the level of green light/red light, go/stop binary directions. The logic attached to the sensor must therefore be sophisticated enough to decide in real time whether the condition is safe or unsafe. On the other hand, a full analysis of the respirator sensor data, including the physiology of the firefighter's breathing pattern and the materials he or she has been exposed to, will require storage of the entire record of sensor values, in such a way that data can be easily correlated.

The importance of developing trust and confidence of the wearers in the usefulness and reliability of these devices, as with any new equipment, was emphasized.

4 SENSOR INTEGRATION AND ENGINEERING

The presenters for this section were Jay Snyder (NIOSH/NPPTL), Paul Greenberg (NASA-Glenn), Arthur Johnson, a professor of Bioengineering at the University of Maryland, and Kathryn Butler (NIST). Their presentations focused on engineering issues relating to the conditions inside of respirator facemasks and how best to design and position sensors to facilitate reliable measurements.

4.1 Sensor Development for ESLI & Its Application to Chemical Detection – Jay Snyder (NIOSH/NPPTL)

The sensor technologies currently under investigation by the End of Service Life Indicator (ESLI) program sponsored by NIOSH/NPPTL are highly relevant to the problem of monitoring respiratory protection. This area was reviewed by Dr. Jay Snyder, who began by raising the issues of what information is useful, what is the best format for communicating it, and how much is too much.

The ESLI program is directed at developing microsensors that can be embedded directly in filter cartridges used in air purifying respirators (APRs) and eventually in powered air purifying respirators (PAPRs) to indicate when target compounds are able to break through as a result of saturation of the filter bed. The two technologies currently being actively pursued are the MEMS electronic system discussed in Section 3.3, consisting of a tiny array of sensors on a chip that could include chemiresistors, cantilevers, and humidity and temperature sensors, and the optical system of photonic crystals presented in Section 3.1. This presentation focused on the engineering challenges of this work, such as the integration of sensors into the filter cartridge, the use of standard electronic devices for packaging, and the testing and evaluation of the ensemble.

Figure 10 shows a prototype respirator equipped with a sensor array integrated into the filter cartridge. The sensors are packaged in a standard TO5 electronics package, a short cylindrical metal case, that is embedded into the cartridge. Data are then communicated across an electrical interface from filter to mask to signal the wearer through ESL indicators. Eventually it is hoped that the sensors may be wireless, so that they may transmit data from anywhere within the filter using radio frequency (RF) signals. Since the filter is a conductive medium, this is not a trivial challenge. The optimal location within the cartridge (in the center? along the side wall?) is yet to be determined. Static electricity is an issue, and grounding straps may be necessary.

Figure 10. Prototype respirator equipped with a sensor integrated into the filter cartridge.

Several sensor integrated cartridges have been assembled in collaboration with multiple respirator manufacturers, and successful tests to detect toluene breakthrough have been carried out. It is expected that this environment is complex enough that multiple sensing modalities will be needed.

4.2 Engineering Considerations – Paul Greenberg (NASA Glenn Research Center)

In his presentation, Dr. Paul Greenberg delineated some of the engineering considerations that would have to be addressed in the design of real-time monitoring of first responder respiratory protection. Recognizing that the harsh environment of a fire and the nature of firefighting would present a severe challenge, he states that "Effective solutions often require creative ways of thinking." Figure 11 shows the "Lick and Stick" Multi-species Leak Detector discussed by Gary Hunter as an example of engineering decision-making in sensor design.

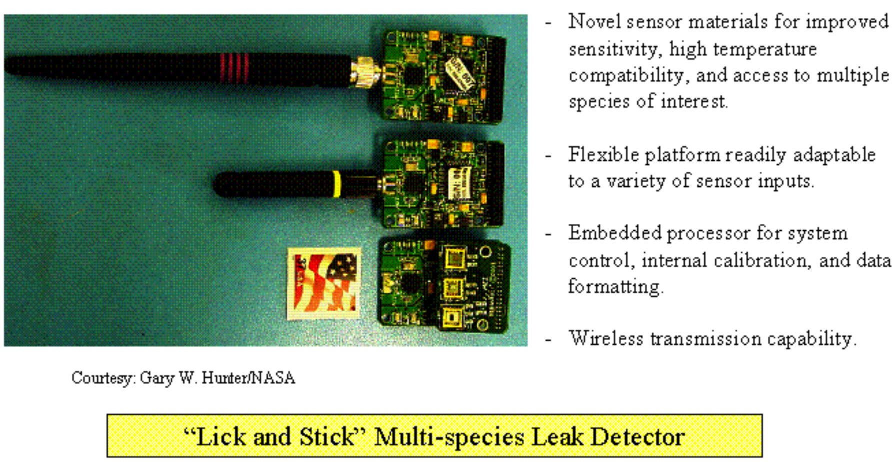


Figure 11. Multi-moment particulate sensor, showing engineering considerations that contributed to its design

Dr. Greenberg's list of engineering considerations for tracking respiratory protection follows:

- Environmental
  - Temperature, humidity, shock, vibration, physical orientation, corrosive, reactive, or flammable surroundings
- Packaging considerations/Physical attributes
  - Size/volume, mass, power consumption, durability
- Application-specific considerations
  - Physical sampling of ambient pressure or flow, avoiding potential biases
  - Conditional sampling – what are the data rate requirements, correlated vs. random sampling
  - Form, fit and function: user compatibility for specific field situation
  - Differences in measurement with location inside mask
- Operational Considerations
  - Data logging and/or wireless transmission; data transfer
  - Internal processing: providing the answer vs. providing raw data
  - Duration of event(s) of interest
  - Overall anticipated service life
  - Reliability
  - Visibility and operability (i.e. user interface)
  - Cost and number of units required
  - Calibration and calibration interval
  - Requirement for internal health status monitoring – "Is my sensor working?"
- Scaling and Fabrication Considerations
  - Physics of scaling – simply making an existing sensor smaller generally doesn't work
  - An alternative or completely new measurement approach may be required
  - This may introduce issues such as materials compatibility or sub-element inter-operability
  - Different or possibly novel methods of fabrication may be required
- Testing considerations
  - Nuisance backgrounds
  - Metrics
  - How good does the sensor need to be?

4.3 Measuring and Visualizing Flows Inside Respiratory Masks – Arthur Johnson (University of Maryland at College Park)

Professor Arthur Johnson informed the workshop about several studies to visualize flow and measure leakage volumes experimentally under laboratory conditions. Although this work was done using Powered Air-Purifying Respirators (PAPRs), which are negative pressure devices, aspects of the results are applicable to firefighter SCBAs.

Figure 12 illustrates the visualization of flow from a headform covered by a loose-fitting PAPR and connected to a breathing machine. The flow paths are visualized by digital video image capture of a glycerol fog that covers nearly the entire face area during all breathing phases. A thread fixed at the mouth identifies whether the phase is inhalation or exhalation, and the flashing of a light emitting diode (LED) helps to time the video frames. The flow field for the loose-fitting PAPR is downward over the face from a fan in back, but the flow is not steady. The delineated flow pathways are contorted, twisted, and multilayered, indicating that measurements of gas concentration and other variables that are being considered for sensor arrays may also not be steady at any given location. This makes it difficult to make correct measurements and highlights the importance of positioning the sensor in a location that represents the actual uptake of firefighter breathing.

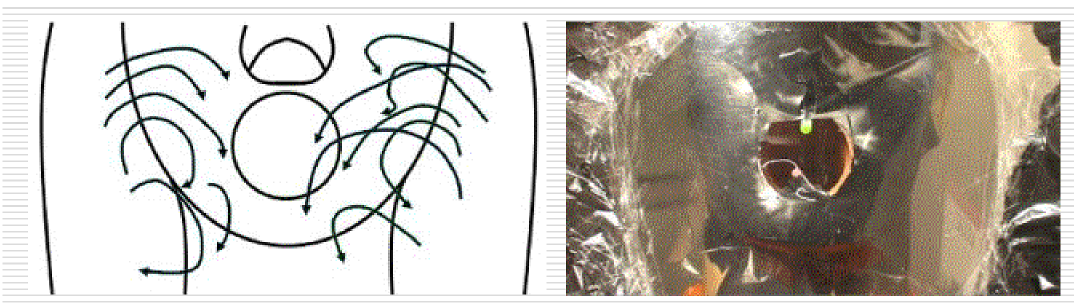


Figure 12. Flow visualization in a loose-fitting PAPR – diagram of flow pathways

The second study looked at inward leakage in tight-fitting PAPRs. Since a significant portion of these facepieces is opaque, flow visualization is difficult. The flow rate from the blower flow rates during inhalation is not constant, and during exhalation flow into the blower has been observed. For this study, flow meters were added to the instrumentation to measure the leakage flow rates and flow volumes, and a bronchoscope failed to detect any inhaled fog at the mouth of the headform.

The third study used glycerol fog and digital video imaging to visualize the flow for ten human subjects in loose-fitting PAPRs. A pneumotach was used to measure volume flow rate through the mouth. As for the headform study, the flow paths were found to be twisted and curled. This can actually add to the respirator protection, since only the contaminants that reach the mouth are important, not simply the contaminants within the mask. Even if contaminants are leaking into the respirator, the longer the flow pathway, the less likely that these contaminants will be inhaled. Given that contaminant concentrations are not uniform, obtaining a representative measure of concentrations is a challenge.

In the fourth study, protection factors were calculated for a headform attached to a breathing machine inside an environment chamber, using CO_2 as a tracer gas, such that the protection factor was based on the amount of CO_2 inhaled. If during exhalation blowers can clean the dead volume within the loose fitting PAPR of contaminants, the protection factor could be improved. The blower effectiveness, or how much of the air within the PAPR is coming from the blower rather than from the outside environment, is the important factor.

4.4 Simulating Flows Inside (and Outside) Respiratory Masks – Kathryn Butler (NIST/BFRL)

Dr. Kathryn Butler demonstrated that computational fluid dynamics (CFD) software tools can be used to simulate the flow inside of the respirator. Given the geometry of the face and the respirator, it is possible to define the three-dimensional space bounded by these surfaces. The flow dynamics are controlled by the breathing pattern applied at the mouth or nose, the locations of entry and exit valves, and the location and size of a defined leak. CFD has the capability of providing information on flow velocity, pressure, gas concentration, particle motion, and other variables throughout the computational space, that can then be visualized in still images and videos.

Figure 13 demonstrates the capability of CFD to describe the flow and pressure fields within a half-facepiece respirator mask during the exhalation phase. The velocity vectors and streamlines show the exhaled breath striking the wall of the respirator across from the mouth. The exhaled gases then flow downward or upward and around to leave through the center valve. Contours of pressure show a maximum on the respirator across from the mouth. The analysis determines the values of all problem variables for the entire volume as a function of time, and therefore gives a much more complete picture of what is occurring than is possible in experiments with discrete sensor measurements. Experiments are critical, however, to validate the analysis and ensure that the results are realistic.

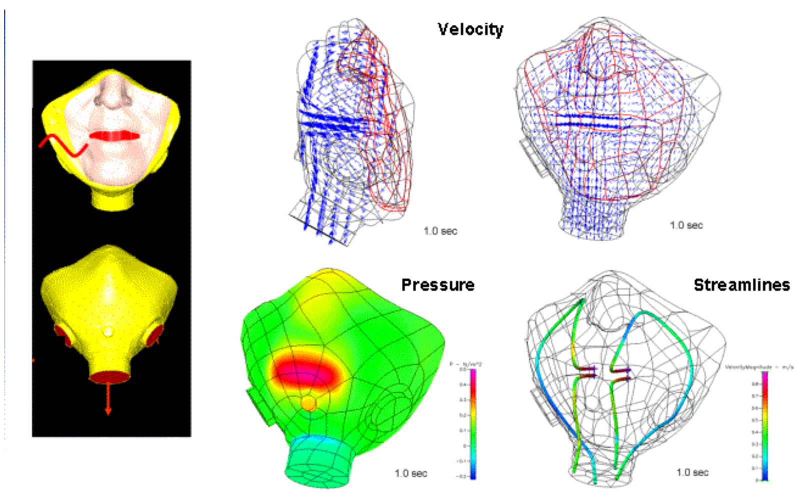


Figure 13. Computational analysis of flow and pressure during exhalation in a half mask.

It is possible to use computational methods to investigate the flow fields and pressure inside a specific respirator for a number of breathing patterns, geometries, and potential leaks, with the goal of determining where within the respirator would be a good location for a sensor to monitor conditions.

Other examples of computational analysis presented in this talk included a study of the effect of an external leak of oxygen from a Closed Circuit SCBA (CC-SCBA) into a near flammable environment[13] and the measurement of fit and discomfort by gradients in contact pressure for a respirator pulled onto a head.

4.5 Discussion

It is clear from the workshop presentations that the basic components of a sensor system for real-time monitoring of respiratory protection for first responders exist. As a minimum, respirator sensors must be compact and self-contained. These requirements have been met by functioning technologies described at this workshop, including miniaturized sensors, multivariate analysis techniques, wireless communication, and power supplies. After this final set of presentations, the discussion centered around the engineering challenges to accomplish the goal of tracking respiratory protection on the fireground.

An important step is to narrow the expectations and scope of the problem to make it more specific, especially for the first stage of implementation of sensor technology for field measurements. What is it that we want to measure? Speakers at this workshop have shown that a number of sensor technologies are available, but the problem space, including species and concentrations, needs to be defined. A list of components of the fire environment includes CO, CO_2, O_2, hydrogen cyanide, hydrogen chloride, chlorine, formaldehyde, SO_2, NO_2, hydrocarbons, water vapor, and particulates. A well-defined initial problem would be to measure some minimum number of gas species, perhaps a single tracer gas or two to three gases of primary importance. For example, CO_2 and O_2 were suggested as good choices. If a laboratory demonstration of the technology is needed with a real person, sulfur hexafluoride, helium, and fluorescent aerosol were mentioned as tracers. Humidity and particulates pose challenges to the measurements – humidity can saturate a sensor and particulates can prevent proper operation. The effects of these confounding factors cannot simply be subtracted out.

The quantities to be measured are affected by the purpose of the measurement. The detection of a leak is a simpler problem than tracking firefighter physiology, for example. Even this goal is non-trivial, however. Multiple sensors or careful sensor placement will be required, since conditions within the respirator, including the pressure, are not uniform. The threshold values that define a leak need to be determined.

The respiratory environment that is acceptable for breathing needs to be defined. OSHA has defined limits for short-term as well as long-term exposure. Is this an appropriate starting place for the protection of the firefighter in his/her "workplace"? Do we want to tell the firefighter when he should get out? Or when he is safe? The capability of the technology must be balanced with the need.

The placement of the sensors is a fundamental question to be resolved. A number of participants suggested placing a sensor outside of the respirator as an initial project. The purpose would be to monitor the firefighter's immediate surroundings and indicate whether it is safe to remove the respirator mask. This doesn't need to be near the face – it could be somewhere on the turnout gear, such as in a pocket to keep it from excessive heat. It was Dawn Bolstad-Johnson's opinion that firefighters would be very interested in such a device. Integrating a sensor into the respirator itself has been demonstrated for the ESLI in a filter cartridge (Figure 10) and for a clear mask in a NASA project carried out seven years ago. For a sensor within the respirator, the most logical position for measuring the contents of a breath would be in front of the mouth or nose. However, this is probably not the most practical location. Another potential placement is on the regulator. The viability of this and other possible solutions could be investigated using computational or experimental means. The most difficult set of measurements would be comparing interior and exterior environments on the fireground. A minimal sensor array within the respirator and a more complete array outside was one of the proposals

The question was raised as to which is the bigger problem for the firefighter (and thus perhaps the problem that should be tackled first): inward leakage or removing the respirator early. Although the positive pressure SCBA tries to compensate for a leak by increasing the flow to the respirator, inward leakage is a concern. The amount of inward leakage occurring during fire operations is unknown. It is observed that in order to pass the fit test firefighters may tighten the mask more than they would in actual practice, making the fit test an uncertain measure of how well the respirators really operate.

In addition to the engineering challenges, the firefighter culture adds another set of considerations. Firefighters are not willing to leave the fireground unless they are out of air. The only way to change this is to install a new standard operating procedure (SOP) and/or Safety Officer oversight, along with consequences for failure to comply. If the intention that the new technology will protect firefighter health is not fully appreciated, awareness that their equipment is recording data may raise concerns that the information may be used against them. It may be seen as introducing a Big Brother aspect to the operations that will not be welcomed.

Finally, the cost of this new technology will certainly be a factor in whether or not it will be adopted.

A suggestion to add a hood to the SCBA to increase dead space that can be protective in nature was made, but it was argued that it would add mass and an extra heat load to the heavily burdened firefighter.

5 CONCLUSIONS

Information presented and discussed in this workshop has highlighted the challenges involved in ensuring that SCBA respirators fit the firefighters who depend on them for protection from hazardous gases and particulates known to be present on the fireground. Because of the difficulties involved in maintaining a good fit, it is likely that the seal between the mask and the face will fail on occasion, especially during times of extreme exertion. If this occurs, the consensus view is that the firefighter is still protected because SCBAs are designed such that the pressure is greater inside the mask than outside so that the net direction of flow is outward. However, as communicated by Professor Johnson and other workshop participants, the flow field inside of a respirator mask is not homogeneous, and the direction of flow changes as a function of location and time. Thus, the possibility that an intermittent leak could develop in a region of the mask where the pressure gradient is small (or even negative), thereby allowing hazardous substances to penetrate the facemask, cannot be completely eliminated. In the context of the sporadic claims (albeit undocumented) of soot penetration ("blow-by") and the expectation that rapid breathing during exertion will reduce the pressure inside the mask, this possibility prompts the conclusion that developing a technology capable of monitoring the respiratory intake of SCBA users, or at the least the fit of their facemasks, should be seriously considered. In addition, as pointed out by workshop participants, microsensors could be used in handheld devices or mounted on turnout gear to enable monitoring of external conditions for the purpose of determining when it is safe for the firefighter to remove his/her mask. This application would be extremely beneficial because SCBAs are cumbersome, so that users tend to remove them as soon as they think it is safe to do so. This behavior can obviously result in serious injury in the absence of the capability of detecting the presence of toxic gases and particulates.

Although the sensor technologies currently being investigated at NIOSH, NASA, NIST, and in the NIOSH ESLI program appear to be sufficiently compact and versatile to be implemented in an SCBA, there are formidable engineering challenges that must be overcome before these technologies can be implemented on a routine basis. These challenges include accounting for the adverse effects that interfering compounds, particulates, temperature extremes, and humidity have on the accuracy and reliability of the measurements. In addition, recognizing the complexity of the flow field within the mask, it is also necessary to investigate where to position the sensors in order to obtain measurements that reflect the respiratory intake of the person using the SCBA.

On the basis of these considerations, the discussion during the workshop led to the recommendation that a program of research directed at providing answers to the following questions should be instituted:

- Does pressure inside of a SCBA face mask ever become less than ambient?
    - Where?
    - Under what conditions?
- Is "blow-by" real and does it indicate that there is a leak?

- What subset of environmental species or particulates actually lead to adverse health effects in firefighters?
    - Gases or particulates?
    - Pressure, sound, or other physical indications of leakage?
    - Is it possible to reduce the number of targets to a small number while still providing the necessary information?
- How sensitive, accurate, and fast do the measurements need to be?
    - What is the nature of a leak?
    - Is there a threshold size?
- How do we develop occupational hygiene (or safe operating) procedures from health effect information?
    - What criteria should be used to decide when the risk to the firefighter is minor?
    - What criteria should be used to decide when to use respirators during overhaul?
    - What gases are absorbed by the hair and skin, and are there any adverse health effects associated with the absorption of these gases?
- Where should the sensors be positioned?
    - Are multiple sensors required to detect leaks?

Once these engineering issues have been resolved, performance evaluations should be conducted to assure potential users of the usefulness and reliability of this technology.

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Appendix A Workshop Agenda

Workshop on
Real-Time Monitoring of Total Inward Leakage of Respiratory Equipment Used by Emergency Responders

Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, Maryland
Friday, May 1, 2009

Meeting Location: Building 101 / Lecture Room B

8:00 Opening Remarks and Agenda – Kathryn Butler, NIST/BFRL

8:30 Session 1: **First Responder Needs**
NIOSH Fit Test Research – Ziqing Zhuang, NIOSH/NPPTL
Fit Testing First Responders – Dawn Bolstad-Johnson, Phoenix Fire Department

9:15 Discussion

10:15 Break

10:30 Session 2: **Sensor Technologies**
Gas Sensing with Porous Silicon Photonic Crystals – Brian King and Michael J. Sailor, UC San Diego
NIST Chemiresistive Microarray Technology – Kurt Benkstein and Steve Semancik, NIST/Physics Laboratory
MEMS Sensor Development for End-of-Service-Life Indicators (ESLI) – Nathan Lazarus and Gary Fedder, Carnegie Mellon University
Ultrasound in Respirators: Concepts and Preliminary Results – William P. King and J. V. Szalajda, NIOSH/NPPTL
Chemical Sensors for Aerospace Applications: From Sensor Platforms to System Application – Gary Hunter, J.C. Xi, P. Greenberg, and P.G. Neudeck, NASA Glenn Research Center, C.C. Liu, Case Western Reserve University, D.B. Makel and B. Ward, Makel Engineering Inc., P. Dutta, Ohio State University, R. VanderWal, USRA at NASA Glenn Research Center, L. Dungan, NASA Johnson Space Center

11:30 Discussion

12:30 Lunch

1:30 Session 3: **Sensor Integration and Engineering**
Sensor Development for ESLI & Its Application to Chemical Detection – Jay Snyder, NIOSH/NPPTL
Engineering Considerations – Paul Greenberg, NASA-Glenn
Measuring and Visualizing Flows Inside Respiratory Masks – Arthur T. Johnson, University of Maryland
Simulating Flows Inside (and Outside) Respiratory Masks – Kathryn Butler, NIST/BFRL

2:30 Discussion

3:30 Break

3:45 Wrap-up and Conclusions – Kathryn Butler, NIST/BFRL

4:30 Close

Appendix B Workshop Registrants and Attendees

Claire Austin	NRC Canada
Nathan Beck	SAIC
Kurt Benkstein	NIST
Dawn Bolstad-Johnson	Phoenix Fire Department
Les Boord	NIOSH/NPPTL
Adam Boussouf	
Djamel Boussouf	Rve Inc.
Keith Brower	Loudoun County Fire, Rescue and Emergency Mgmt.
Rodney Bryant	NIST
Nelson Bryner	NIST
Kathryn Butler	NIST
Karen Coyne	U.S. Army ECBC
Dennis Ertel	SOMA
Ken Farmer	National Fire Academy
Kenneth (Beau) Farmer	TSI Inc.
Kenneth Gaiser	City of Jackson
Paul Greenberg	NASA-Glenn
Gary Hunter	NASA
Shaya Jamshidi	SAIC
Arthur Johnson	UMd College Park
Brian King	UC San Diego
William P. King	NIOSH/NPPTL
Adam Kochanski	University of Utah
Nathan Lazarus	CMU
Nathan Marsh	NIST
Jennifer Marshall	NIST
Jack Mawhinney	Hughes Associates, Inc.
Stephan B. Miller	University of Houston
Mitch Molenof	D.C. Fire Department
Carlo Alberto Monti	ICS SRL
Marc Nyden	NIST
William Reinhard	Fire Service Instructor / Course Development
Peter Rutkowski	Mine Safety Appliances Company
Dongil Shin	
Lei Song	University of Science and Technology of China
Jay Snyder	NIOSH/NPPTL
Natalia Stakhiv	OSHA
John Steelnack	OSHA
James Stewart	NIST-OLES
John Szalajda	NIOSH/NPPTL
Qiyuan Xie	University of Science and Technology of China
Ziqing Zhuang	NIOSH/NPPTL

Appendix C NIOSH Fit Test Research – Ziqing Zhuang (NIOSH/NPPTL)

NIOSH Fit Test Research

Ziqing Zhuang, PhD

National Institute for Occupational Safety and Health (NIOSH)
Centers for Disease Control and Prevention (CDC)
U.S. Department of Health and Human Services
Pittsburgh, PA USA

Workshop on Real Time Monitoring of Respiratory Protective Equipment Used by Emergency Responders

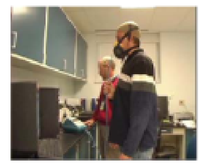
May 1, 2009

National Institute of Standards and Technology

Gaithersburg, Maryland

Fit Testing Regulation

Before an employee uses any respirator with a **negative or positive pressure tight-fitting facepiece**, the employee must be fit tested with the same make, model, style, and size of respirator that will be used (OSHA 29 CFR 1910.134).



Workplace Fit Testing Requirements

- Employees using tight-fitting facepiece respirators must pass an appropriate fit test:
  - prior to initial use,
  - whenever a different respirator facepiece (size, style, model or make) is used, and
  - at least annually thereafter
- An additional fit test must be conducted whenever the employee reports, or the employer, physician or licensed health care professional (PLHCP) makes visual observations of changes in the employee's physical condition (e.g., facial scarring, dental changes, cosmetic surgery, or obvious change in body weight) that could affect respirator fit

Qualitative Fit Test (QLFT)

- A pass/fail fit test to assess the adequacy of respirator fit that relies on the individual's response to the test agent
- QLFT may only be used to fit test negative pressure APRs that must achieve a fit factor of 100

Quantitative Fit Test (QNFT)

An assessment of the adequacy of respirator fit by numerically measuring the amount of leakage into the respirator.

Fit Factor

Fit factor is a quantitative estimate of the fit of a particular respirator to a specific individual, and typically is calculated as:

$$\frac{\text{[Concentration of a substance in ambient air]}}{\text{[Concentration inside the respirator when worn]}}$$

Example:

$$\frac{\text{[6000 particles/CC in ambient air]}}{\text{[30 particles/CC inside the respirator]}}$$

Fit Factor = 200

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Determining the Fit Factor

- **A set of exercises is performed during a fit test**
- **Fit factor is calculated for each exercise and an overall fit factor is calculated using the harmonic mean**
- **If the fit factor is determined to be equal to or greater than 100 for tight-fitting half facepieces or equal to or greater than 500 for tight-fitting full facepieces, the QNFT has been passed with that respirator**

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The fit test must be administered using an OSHA-accepted QLFT or QNFT protocol

- QLFT Protocols:
  - Isoamyl acetate
  - Saccharin
  - Bitrex
  - Irritant smoke (NIOSH does not endorse)
- QNFT Protocols:
  - Generated Aerosol (corn oil, salt)
  - Condensation Nuclei Counter (PortaCount)
  - Controlled Negative Pressure (CNP) (Dynatech FitTester 3000)
  - Controlled Negative Pressure (CNP) REDON (Dynatech FitTester 3000)

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Assigned Protection Factor (APF)

The workplace level of respiratory protection that a respirator or class of respirators is expected to provide to employees when the employer implements a continuing, effective respiratory protection program as specified in OSHA 29 CFR 1910.134

OSHA Assigned Protection Factors (APFs)

Type of respirator	Quarter Mask	Half mask	Full facepiece	Helmet/ hood	Loose-fitting facepiece
1 Air-Purifying Respirator	5	10[1]	50	NA	NA
2 Powered APR	-	50	1000	25/1000[2]	25
3 Supplied Airline Respirator	-				
•Demand mode		10	50	NA	NA
•Continuous-flow		50	1000	25/1000[2]	25
•Pressure-demand		50	1000	NA	NA
4 SCBA:	-				
•Demand mode		10	50	50	NA
•Pressure-demand		NA	10,000	10,000	NA

[1] *This APF category includes filtering facepieces, and half masks with elastomeric facepieces.*

[2] *Must be demonstrated by Manufacturer that respirator can meet APF of 1,000*

Is Fit Testing an Art or Science?

- It's an Art as well as Science

- Laboratory test
- Workplace protection
- Safety margin

Why Fit Testing? - One Size Does Not Fit All

- **Appearances are deceiving**
  - Face seal leakage may not be obvious from visual observation
- **Consequences of poor fit can be significant**
  - Illness and death
- **Regulations**

Why Fit Testing? - Best Way to Assess Fit

- Quantitative and qualitative methods
- Correlation to actual exposures
- Improved worker protection

What Variables Affect Respirator Fit?

- Variations in fit factors
  - With the same person
  - Among different people
  - Among respirator models
  - Among test methods
- Exercise regimes
- Fit test panel

What Is the Focus of NIOSH Research?
- Improve Science to increase worker safety and health

- Validate fit test methods
- Characterize worker faces
- Define new procedures

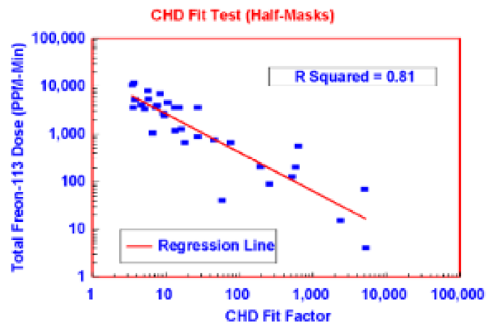
What is the focus? - Validate Fit Test Methods

- Qualitative and quantitative fit test methods
  - Half-facepiece respirators
- Correlation to exposure
  - Biomarker
  - Actual workplace

Coffey et al., 1998b

Correlation between Fit Factor and Actual Exposure

Continuous High Flow Deep Probe (CHD) Fit Test (Half-masks)



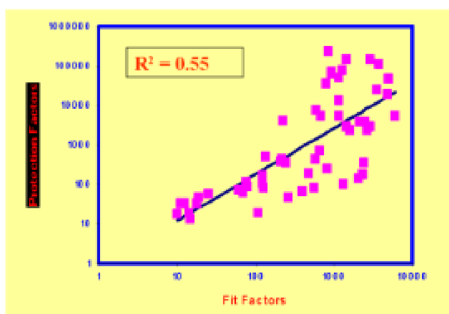
Coffey et al., 2002

Comparison of the Accuracy of Fit test Methods for Filtering Facepiece Respirators

Fit-Test Method	Alpha Error	Beta Error
Accuracy Goal	*≤ 50%*	*≤ 5%*
Bitrex	**51%**	**11%**
Saccharin	**56%**	**9%**
N95-Companion	**57%**	**9%**
Ambient Aerosol	**75%**	**4%**
Generated Aerosol	**84%**	**3%**

Zhuang et al., 2003

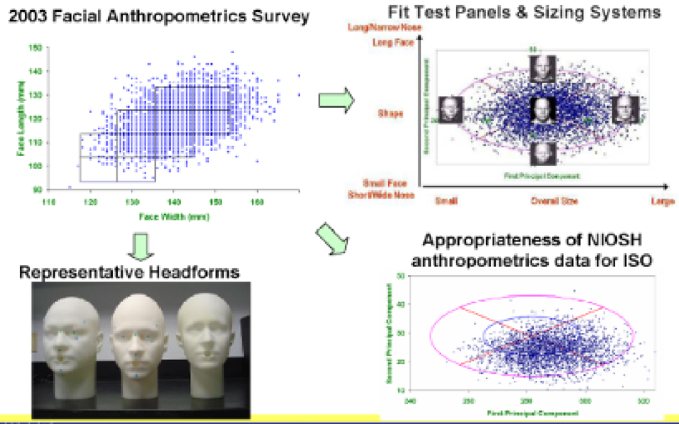
Correlation between Fit Factors and Protection Factors Measured at a Steel Foundry (Half-Masks)



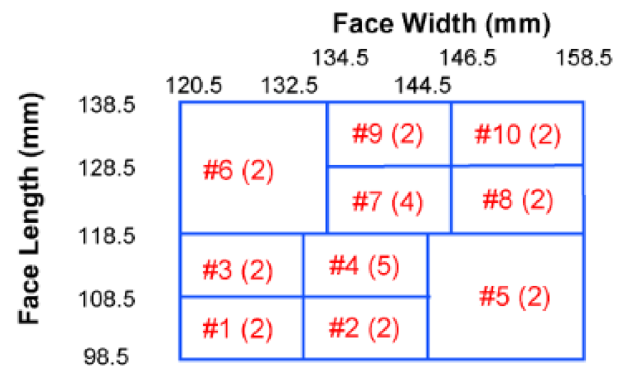
What is the focus? - Characterize Worker Faces

- **Develop an anthropometric database of respirator users**
- **Evaluate the applicability of the Los Alamos National Laboratory (LANL) respirator fit test panels**
- **Investigate correlation between facial dimensions and respirator fit**
- **Redefine respirator fit test panels**
- **Develop new sizing systems**

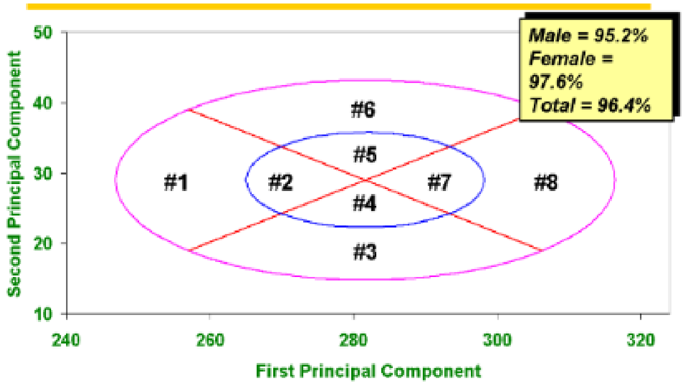
Facial Anthropometrics Research



NIOSH Bivariate Panel



NIOSH Principal Component Analysis (PCA) Panel



What is the focus? - Define New Procedures

- **Multiple donnings**
- **Exercise regimes**
  - Number of exercises
  - Order of exercises
  - Duration of exercises
  - Type of exercises

Future Research on Real Time Monitoring

- Ambient particle measurement
- Pressure drop measurement
- Surface temperature measurement
- CO_2 measurement

Journal Publications

1. Coffey CC, Lawrence RB, Zhuang Z, Duling MG, and Campbell DL [2006]. Errors associated with three methods of assessing respirator fit. Journal of Occupational and Environmental Hygiene 3: 44-52.
2. Coffey CC, Lawrence RB, Campbell DL, Zhuang Z, Calvert CA, and Jensen PA [2004]. Fitting characteristics of eighteen N95 filtering-facepiece respirators. Journal of Occupational and Environmental Hygiene, 1: 262-271.
3. Zhuang Z, Coffey CC, Jensen PA, Campbell DL, Lawrence RB, and Myers WR [2003]. Correlation between quantitative fit factors and protection factors measured under actual workplace environments at a steel foundry. American Industrial Hygiene Association Journal, 64: 730-738.
4. Coffey CC, Lawrence RB, Zhuang Z, Campbell DL, Jensen PA, and Myers WR [2002]. Comparison of five methods for fit-testing N95 filtering-facepiece respirators. Applied Occupational and Environmental Hygiene, 17(10): 723-730.
5. Coffey, C.C., D.L. Campbell, W.R. Myers, and Z. Zhuang: Comparison of six respirator fit-test methods with an actual measurement of exposure: part II - method comparison testing. American Industrial Hygiene Association Journal, 59(12):862-870 (1998b).
6. Coffey, C.C., D.L. Campbell, W.R. Myers, Z. Zhuang, and S. Das: Comparison of six respirator fit-test methods with an actual measurement of exposure: part I - protocol development. American Industrial Hygiene Association Journal, 59(12):852-861 (1998a).

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Journal Publications (Continued)

7. Zhuang Z, Guan J, Hsiao H, and Bradtmiller B [2004]. Evaluating the Representativeness of the LANL Respirator Fit Test Panels for the Current U.S. Civilian Workers. Journal of the International Society for Respiratory Protection, 21(III-IV):83-93.
8. Zhuang Z and Bradtmiller B [2005]. Head-and-Face Anthropometric Survey of U.S. Respirator Users. J Occup. Environ. Hyg., 2, 567-577.
9. Zhuang Z, Coffey CC, and Berry Ann R [2005]. The effect of subject characteristics and respirator features on respirator fit. J Occup. Environ. Hyg. 2, 641-649.
10. Roberge R, Zhuang Z, Stein, L [2006] Association of Body Mass Index with Facial Dimensions for Defining Respirator Fit Panels. Journal of the International Society for Respiratory Protection, 23(I-II):44-52.
11. Zhuang Z, Bradtmiller B, and Shaffer RE [2007]. New Respirator Fit Test Panels Representing the Current U.S. Civilian Workforce. J Occup. Environ. Hyg. 4, 647-659.
12. Zhuang Z, Groce D, Ahlers HW, Iskander W, Landsittel D, Guffey S, Benson S, Viscusi DJ and Shaffer RE [2008]. Correlation between Respirator Size and Respirator Fit Test Panel Cells. J Occup. Environ. Hyg. 5, 617-628.

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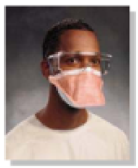
Quality Partnerships Enhance Worker Safety & Health

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Disclaimer:

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Thank you

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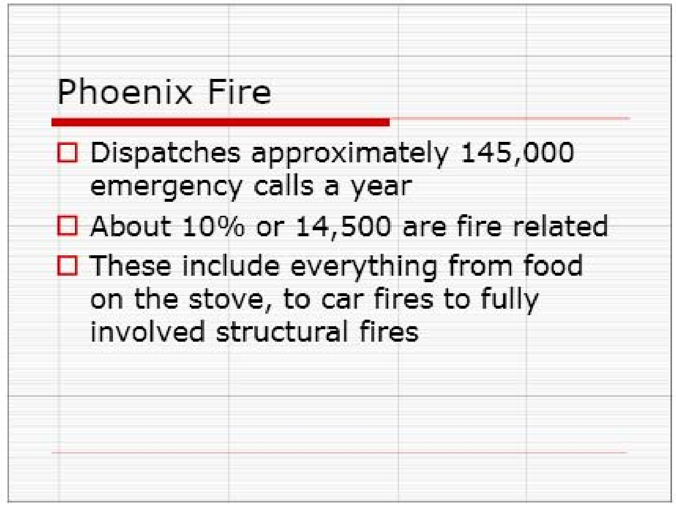
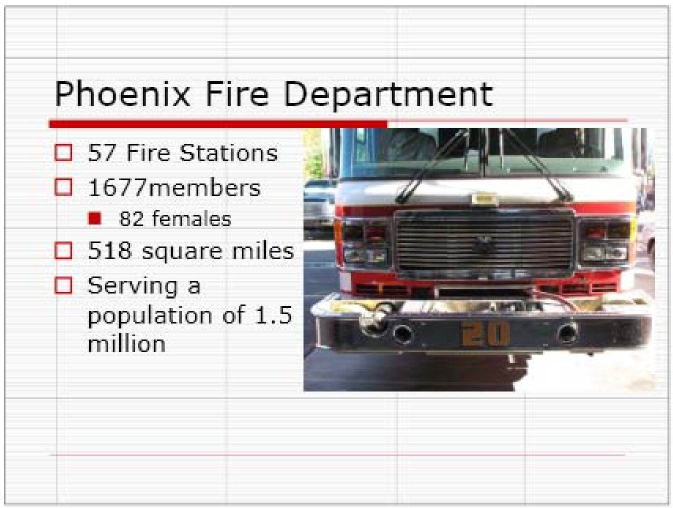
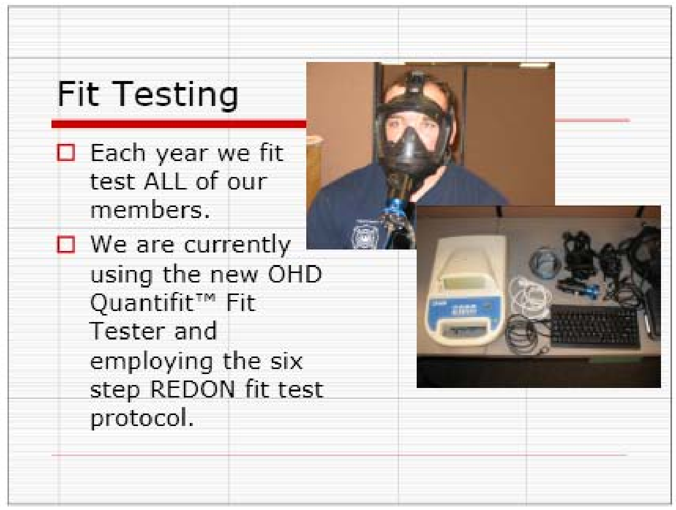
Appendix D Fit Testing First Responders – Dawn Bolstad-Johnson (Phoenix Fire Department)







Fit Testing

- Facial features often affect the seal and fit test.
  - Hair lines
  - Narrow faces
  - High cheekbones
  - Facial scarring
  - Long chins
- If members are having a hard time getting a passing score, they often will cinch down the head harness a little more.

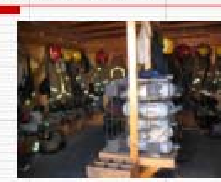
Fit Testing 2009

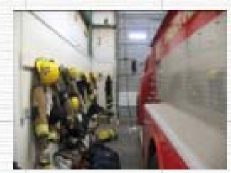
- Out of over 1700 fit tests, we had about 10 individuals fail their fit tests
- These individuals are directed to go to our AIR ROOM to be refitted.
- This number is significantly lower than last year and may be due to the fact that we are in the process of changing our SCBA to another supplier. We are seeing better "fits" with the new mask.

Storage of face masks

Storage of the face masks

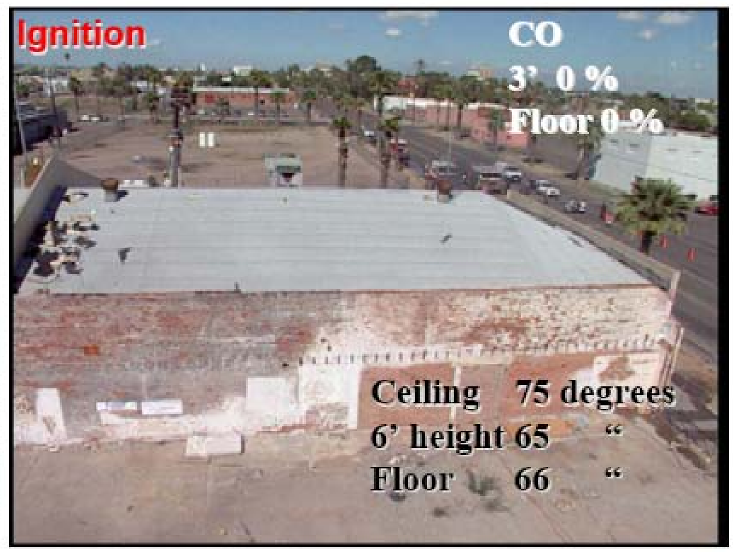
- Storage issues can affect the face piece fit.
- Storage in the trucks, the bays or even in sheds where there are not environmental controls could affect the integrity of the mask itself.

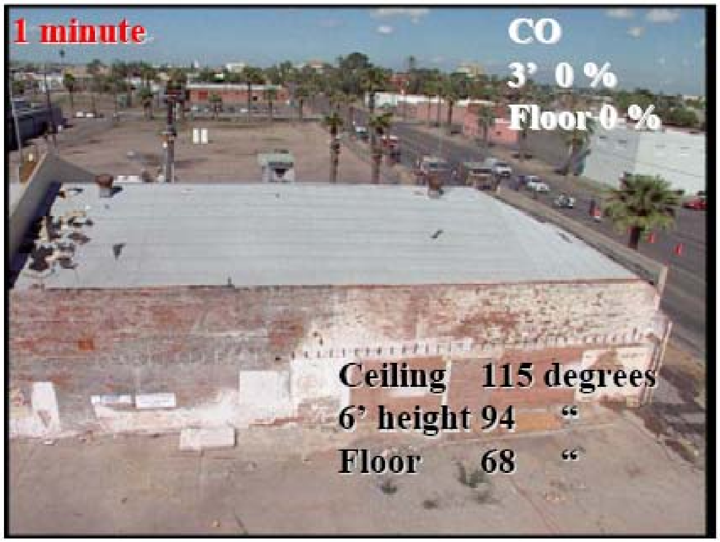


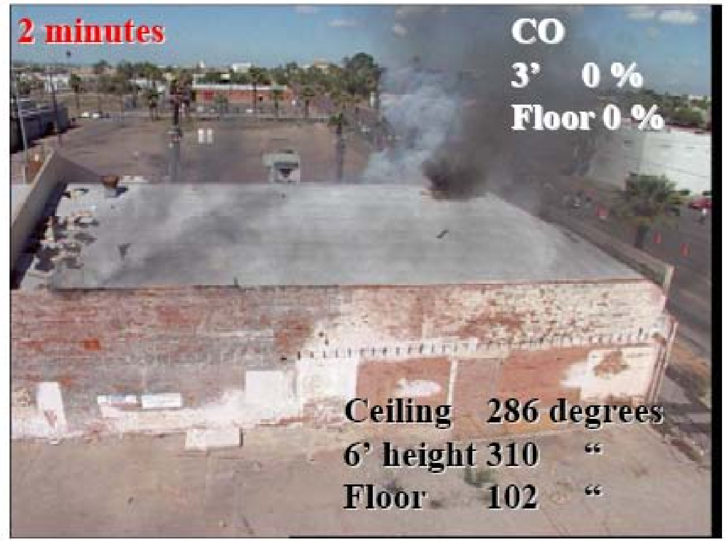



BELLAIR
FURNITURE
6542

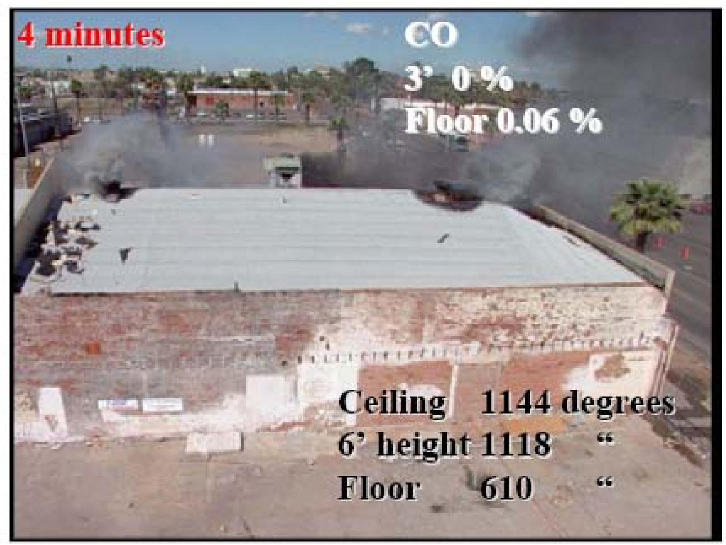

NIST Study in Phoenix

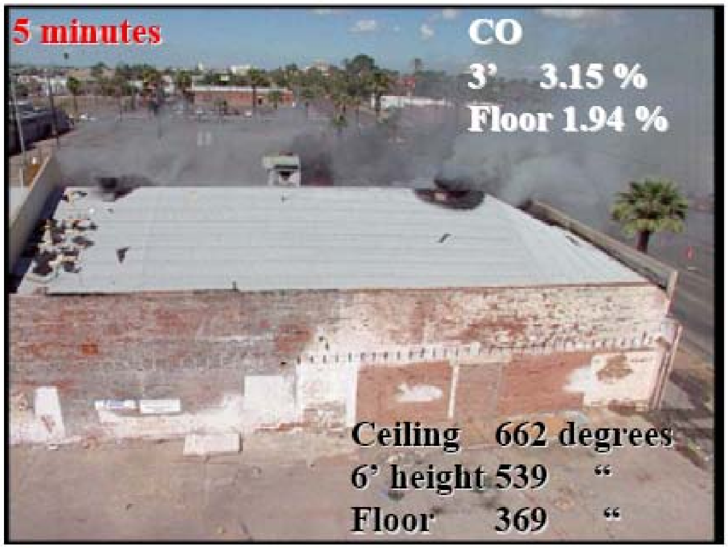


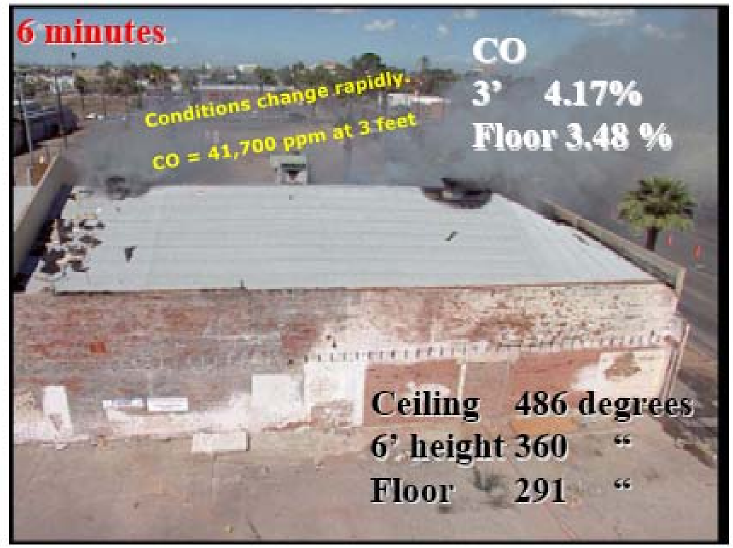

1 minute
CO
3’ 0 %
Floor 0 %
Ceiling 115 degrees
6’ height 94 “
Floor 68 “

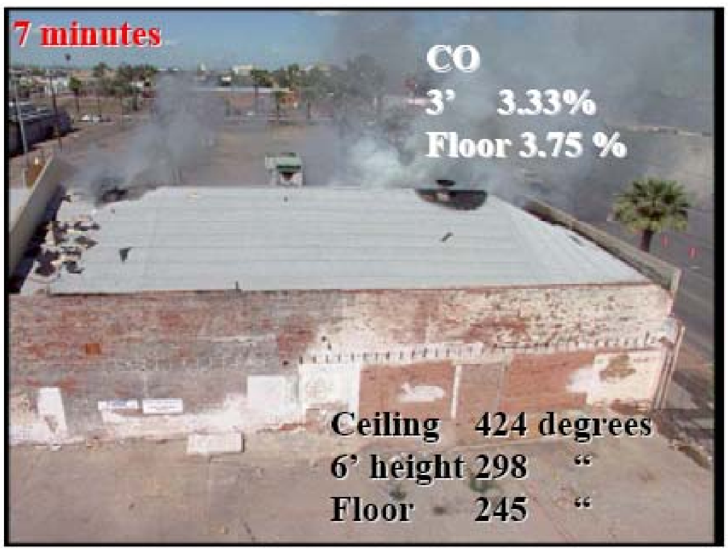

2 minutes
CO
3’ 0 %
Floor 0 %
Ceiling 286 degrees
6’ height 310 “
Floor 102 “

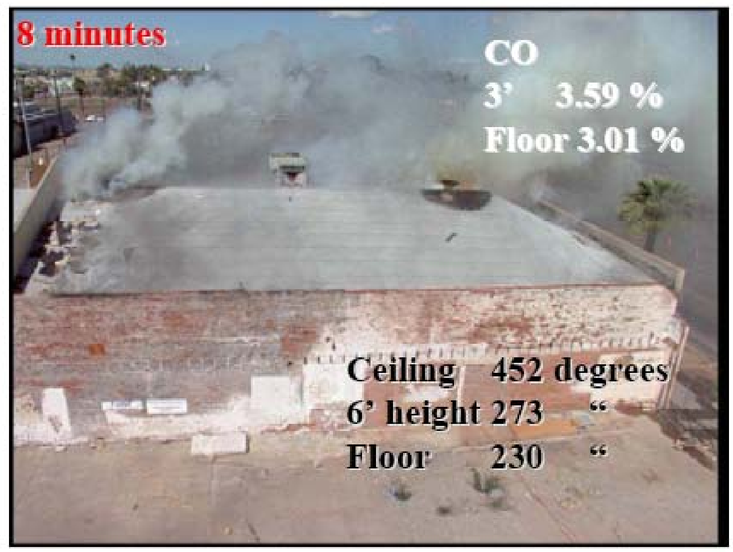

3 minutes
CO
3’ 0 %
Floor 0 %
Ceiling 1242 degrees
6’ height 1342 “
Floor 195 “

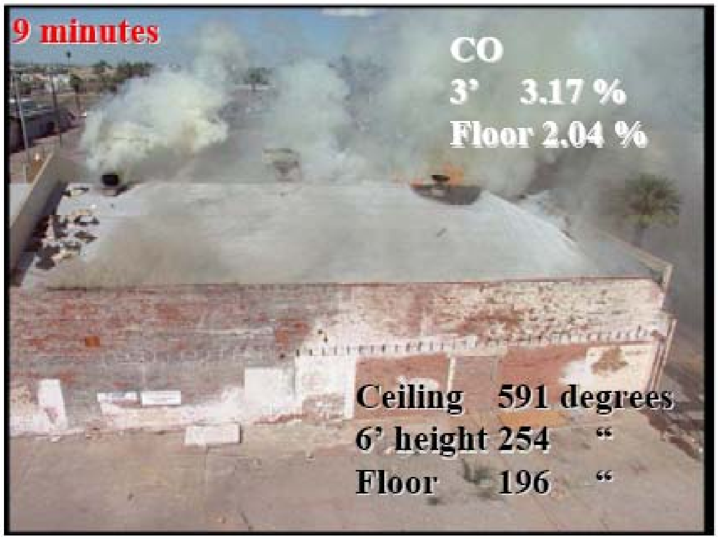

4 minutes
CO
3’ 0 %
Floor 0.06 %
Ceiling 1144 degrees
6’ height 1118 “
Floor 610 “

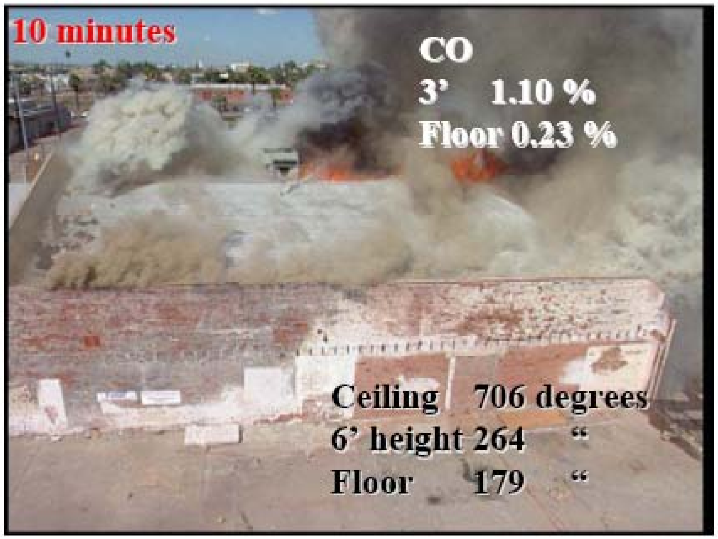

5 minutes
CO
3’ 3.15 %
Floor 1.94 %
Ceiling 662 degrees
6’ height 539 “
Floor 369 “


6 minutes
CO
3’ 4.17%
Floor 3.48 %
Conditions change rapidly.
CO = 41,700 ppm at 3 feet
Ceiling 486 degrees
6’ height 360 “
Floor 291 “


7 minutes
CO
3’ 3.33%
Floor 3.75 %
Ceiling 424 degrees
6’ height 298 “
Floor 245 “


8 minutes
CO
3’ 3.59 %
Floor 3.01 %
Ceiling 452 degrees
6’ height 273 “
Floor 230 “





Conditions during firefighting that may affect respirator fit

- Hot – face sweaty
- Limited (if any) vision- huge potential to bump into fixed objects or debris causing mask to move

Inward Leakage?

- Some firefighters have described "Blow by" where soot is entering their mask during a good fire.
- This phenomena has not been confirmed.

Confounders

- Firefighters wait until the last minute to "click in" their regulators.
- Removing SCBA during overhaul could lead to symptoms such as "black boogers" or soot deposits on the face.

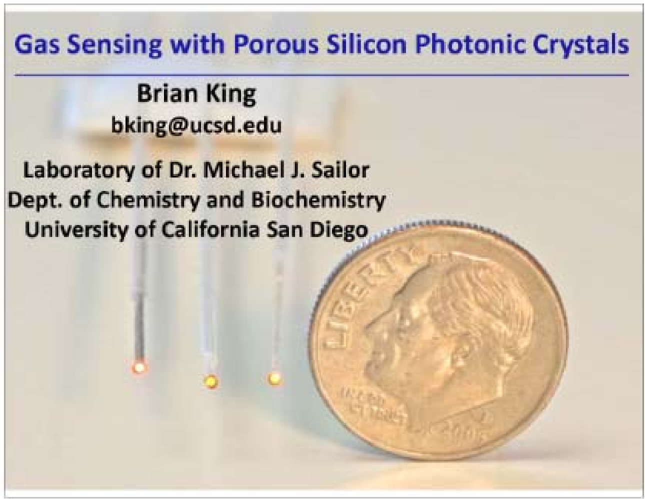
Sensor Needs

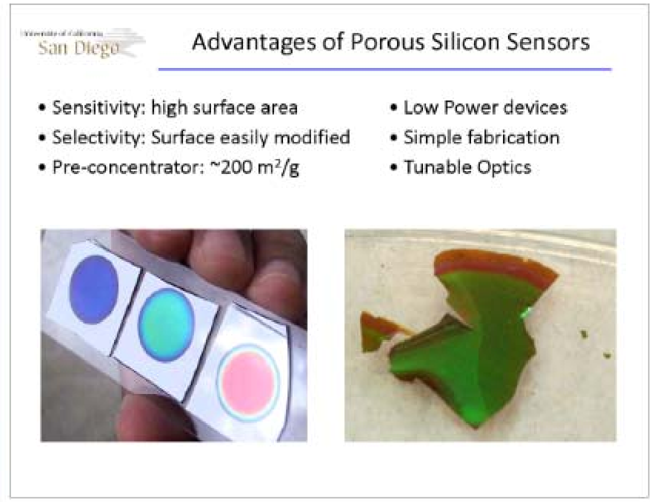
- If the mask does get bumped, the mask may go into negative pressure for a few seconds.
  - How would the sensor respond if the problem "corrected" itself?
- If there are small leaks around the face seal, additional air may be consumed to maintain positive pressure.
  - How would the sensor identify and respond to the small changes.

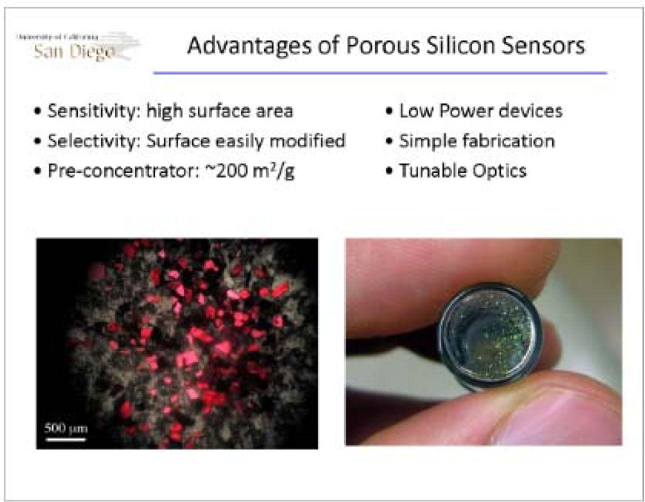
Questions -

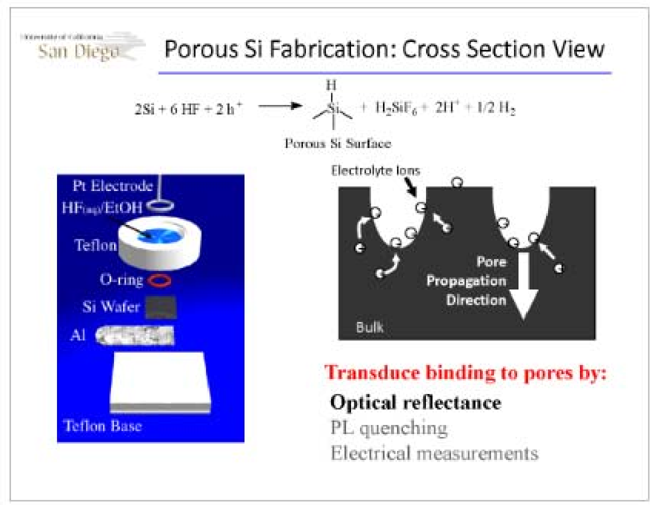
- Thank you

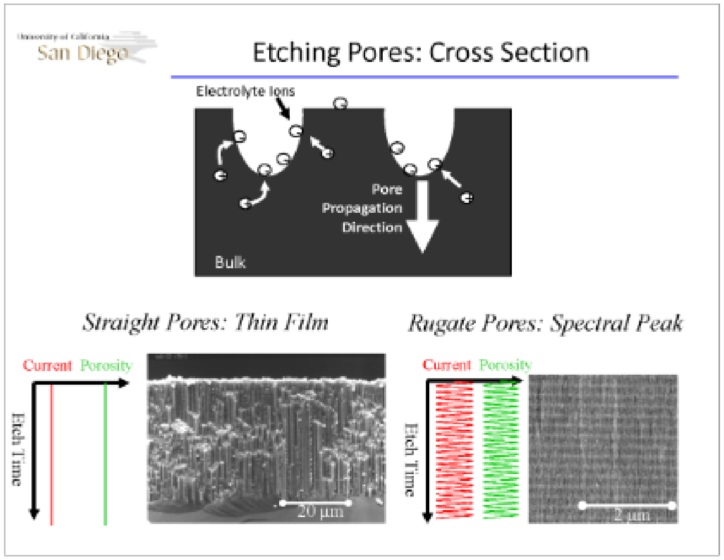
Appendix E Gas Sensing with Porous Silicon Photonic Crystals – Brian King (University of California San Diego)

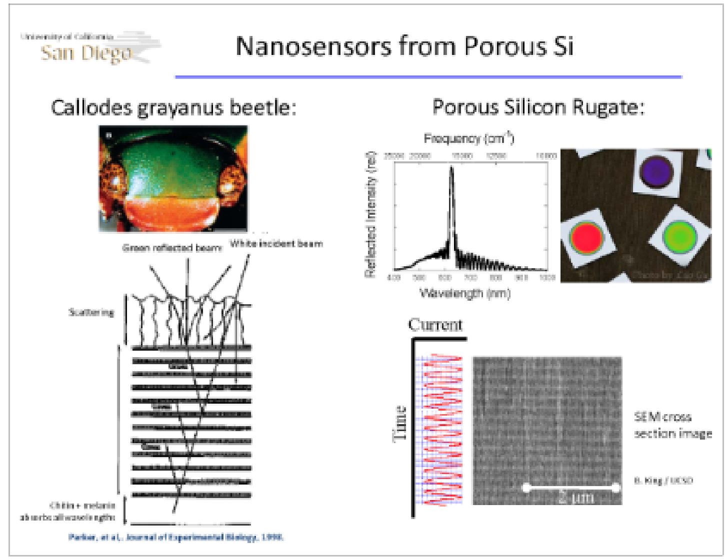


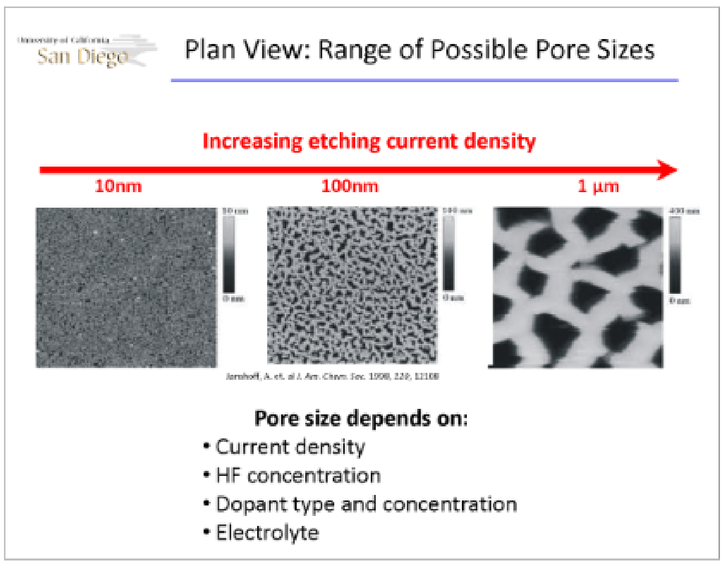


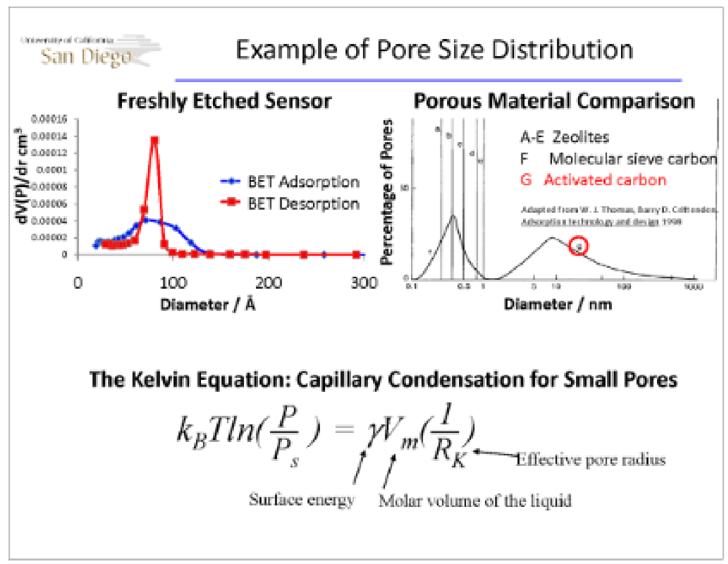


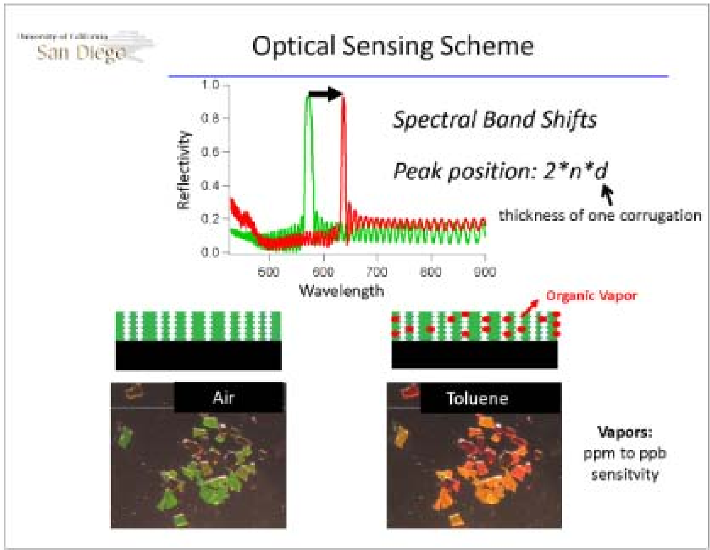


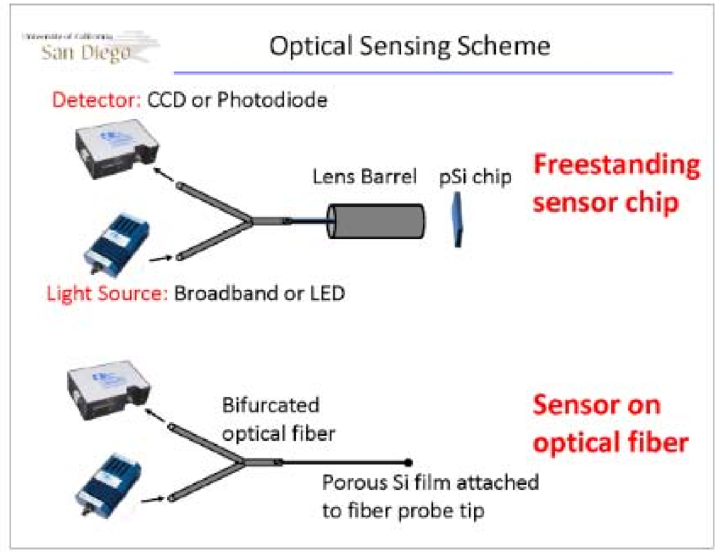

Etching Pores: Cross Section
Electrolyte Ions
Pore
Propagation
Direction
Bulk
Straight Pores: Thin Film
Rugate Pores: Spectral Peak
Current Porosity
Etch Time
20 µm
Current Porosity
Etch Time
2 µm

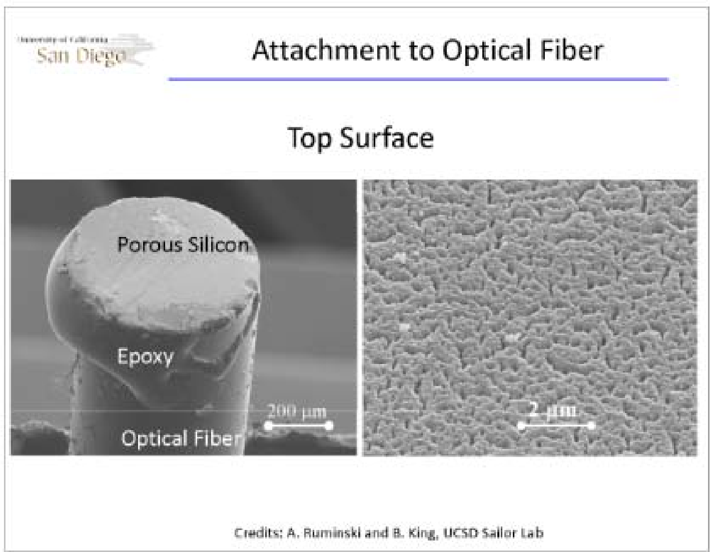

Nanosensors from Porous Si
Callodes grayanus beetle:
Porous Silicon Rugate:
Frequency (cm-1)
Reflected Intensity (rel)
Wavelength (nm)
Green reflected beam
White incident beam
Scattering
Current
Time
SEM cross
section image
2 µm
Parker, et al., Journal of Experimental Biology, 1998.

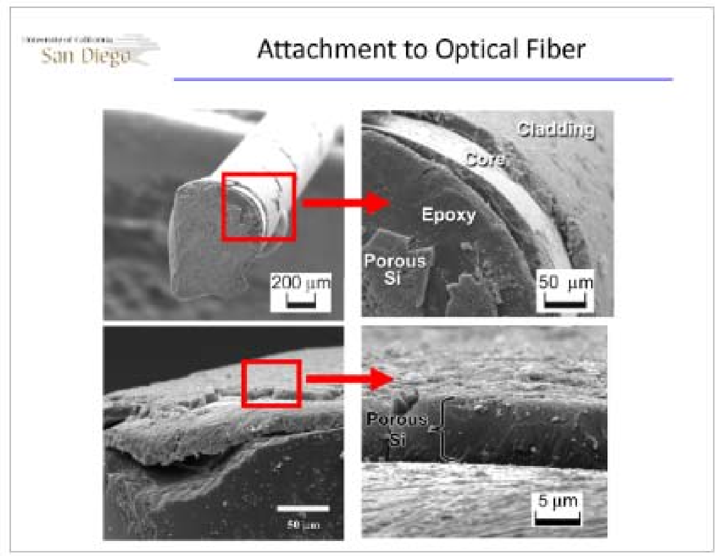

Plan View: Range of Possible Pore Sizes
Increasing etching current density
10nm
100nm
1 µm
Pore size depends on:
• Current density
• HF concentration
• Dopant type and concentration
• Electrolyte


Example of Pore Size Distribution
Freshly Etched Sensor
Porous Material Comparison
dV(P)/dr cm3
BET Adsorption
BET Desorption
Diameter / Å
Percentage of Pores
A-E Zeolites
F Molecular sieve carbon
G Activated carbon
Diameter / nm
The Kelvin Equation: Capillary Condensation for Small Pores
kBTln(P/Ps) = γVm(1/RK)
Effective pore radius
Surface energy
Molar volume of the liquid

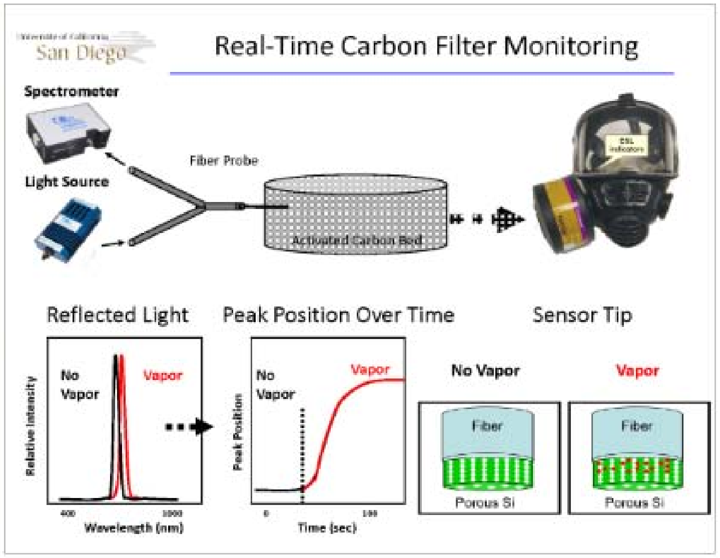

University of California San Diego
Optical Sensing Scheme
Spectral Band Shifts
Peak position: 2*n*d
thickness of one corrugation
Reflectivity
1.0
0.8
0.6
0.4
0.2
0.0
500
600
700
800
900
Wavelength
Organic Vapor
Air
Toluene
Vapors:
ppm to ppb
sensitvity

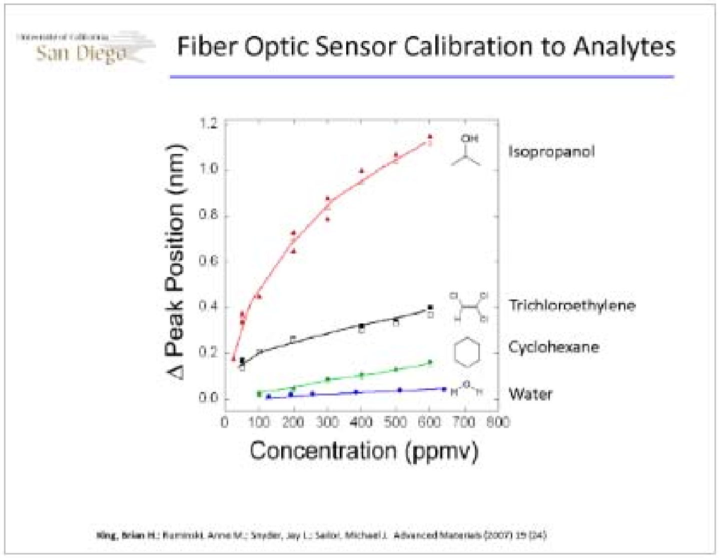

University of California San Diego
Optical Sensing Scheme
Detector: CCD or Photodiode
Lens Barrel
pSi chip
Freestanding sensor chip
Light Source: Broadband or LED
Bifurcated
optical fiber
Sensor on optical fiber
Porous Si film attached
to fiber probe tip

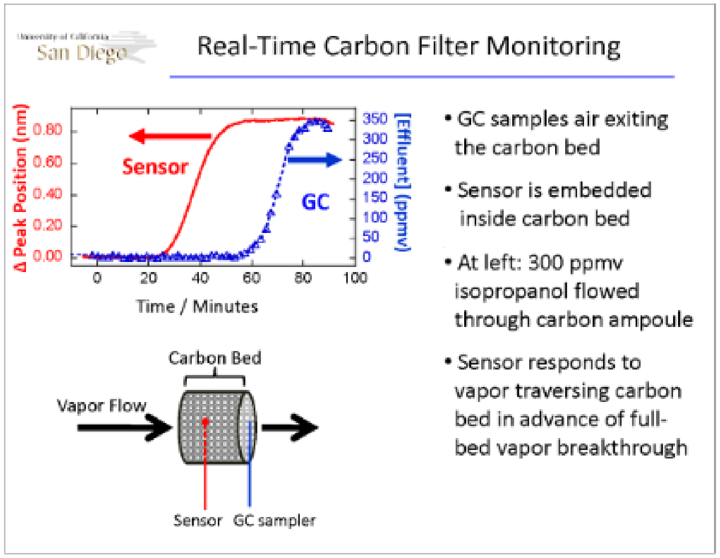

University of California San Diego
Attachment to Optical Fiber
Top Surface
Porous Silicon
Epoxy
Optical Fiber
200 µm
2 µm
Credits: A. Ruminski and B. King, UCSD Sailor Lab

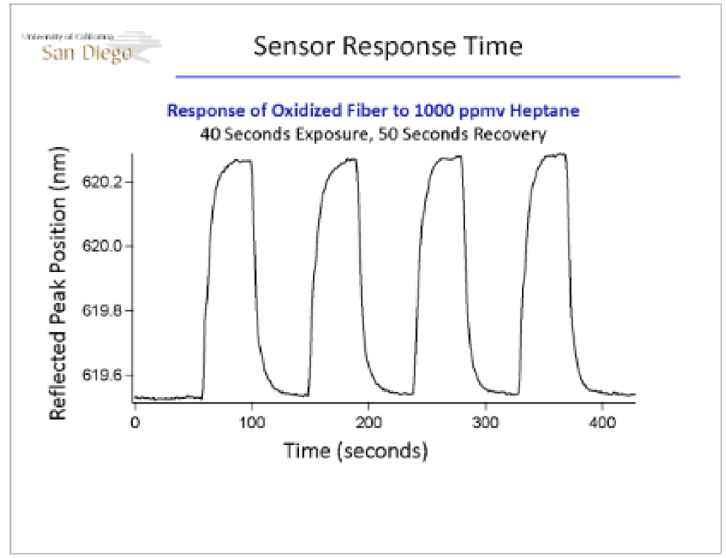

University of California San Diego
Attachment to Optical Fiber
Cladding
Core
Epoxy
Porous
Si
200 µm
50 µm
Porous
Si
5 µm

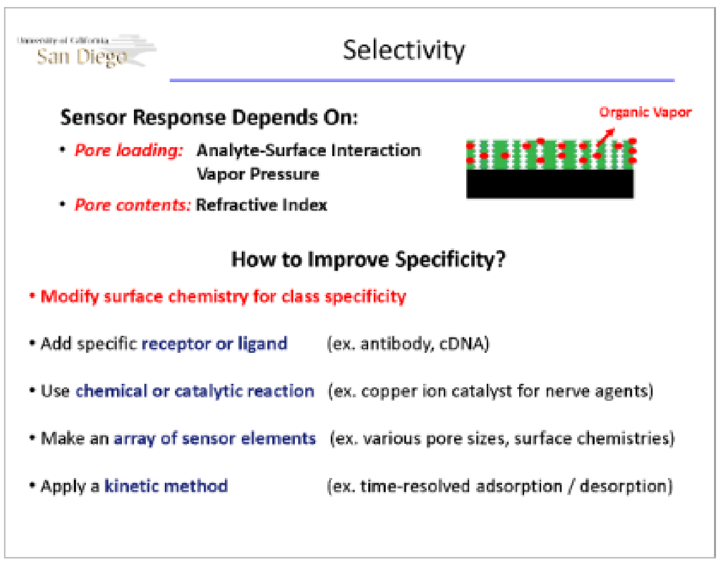

UNITED STATES OF AMERICA
ONE DIME

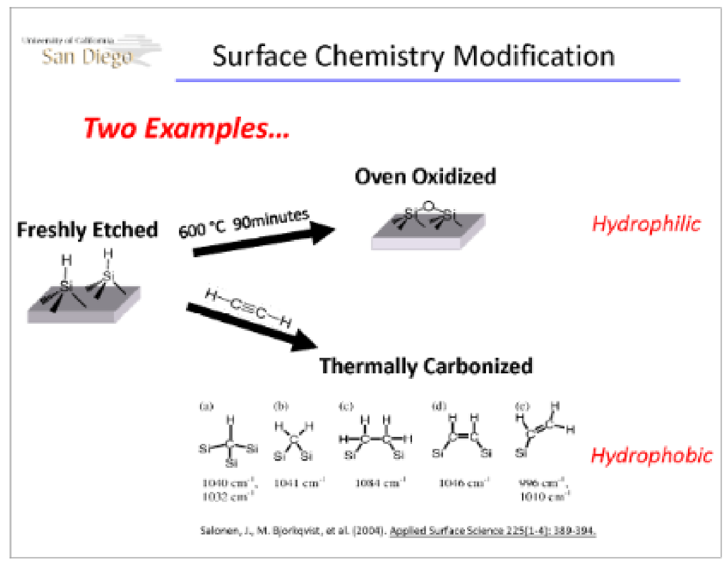

San Diego
Real-Time Carbon Filter Monitoring
Spectrometer
Light Source
Fiber Probe
Activated Carbon Bed
Reflected Light
Peak Position Over Time
Sensor Tip
No Vapor
Vapor
Relative Intensity
Wavelength (nm)
Peak Position
Time (sec)
No Vapor
Vapor
Fiber
Porous Si
Fiber
Porous Si

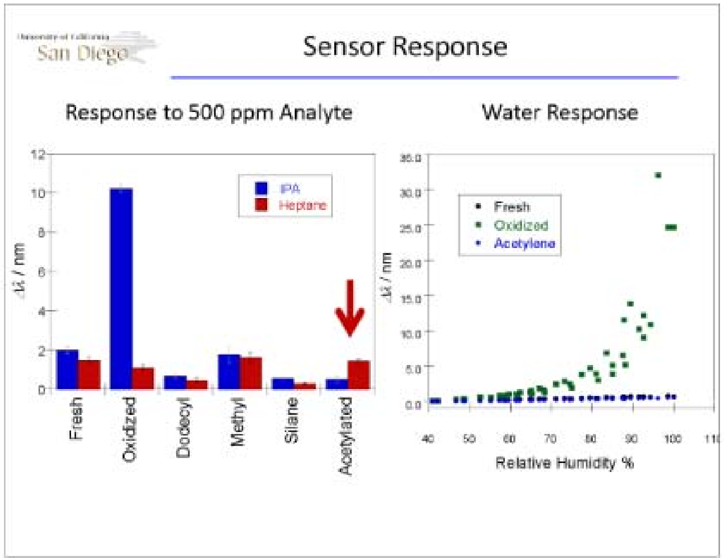

San Diego
Fiber Optic Sensor Calibration to Analytes
Δ Peak Position (nm)
Concentration (ppmv)
Isopropanol
Trichloroethylene
Cyclohexane
Water
King, Brian H.; Ruminski, Anne M.; Snyder, Jay L.; Sailor, Michael J. Advanced Materials (2007) 19 (24)


University of California San Diego
Real-Time Carbon Filter Monitoring
Δ Peak Position (nm)
0.80
0.60
0.40
0.20
0.00
Sensor
GC
350
300
250
200
150
100
50
0
[Effluent] (ppmv)
0
20
40
60
80
100
Time / Minutes
Carbon Bed
Vapor Flow
Sensor
GC sampler
• GC samples air exiting the carbon bed
• Sensor is embedded inside carbon bed
• At left: 300 ppmv isopropanol flowed through carbon ampoule
• Sensor responds to vapor traversing carbon bed in advance of full-bed vapor breakthrough

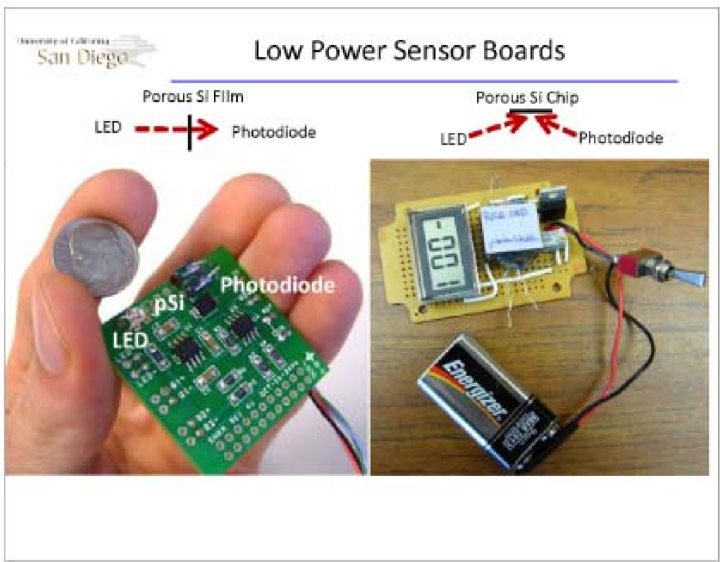

University of California San Diego
Sensor Response Time
Response of Oxidized Fiber to 1000 ppmv Heptane
40 Seconds Exposure, 50 Seconds Recovery
Reflected Peak Position (nm)
620.2
620.0
619.8
619.6
0
100
200
300
400
Time (seconds)

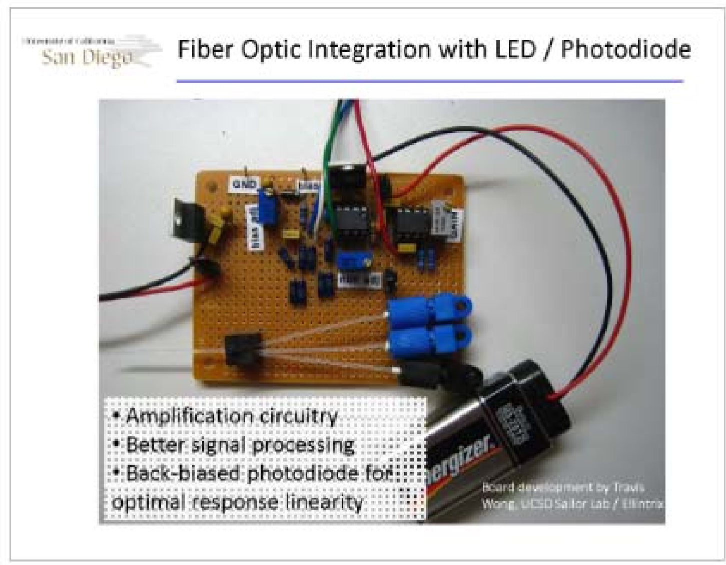

University of California San Diego
Selectivity
Sensor Response Depends On:
• Pore loading: Analyte-Surface Interaction
Vapor Pressure
• Pore contents: Refractive Index
Organic Vapor
How to Improve Specificity?
• Modify surface chemistry for class specificity
• Add specific receptor or ligand (ex. antibody, cDNA)
• Use chemical or catalytic reaction (ex. copper ion catalyst for nerve agents)
• Make an array of sensor elements (ex. various pore sizes, surface chemistries)
• Apply a kinetic method (ex. time-resolved adsorption / desorption)


University of California San Diego
Surface Chemistry Modification
Two Examples…
Oven Oxidized
Freshly Etched
600 °C 90minutes
Hydrophilic
H—C≡C—H
Thermally Carbonized
Hydrophobic
Salonen, J., M. Bjorkqvist, et al. (2004). Applied Surface Science 225(1-4): 389-394.


San Diego
Sensor Response
Response to 500 ppm Analyte
Water Response
IPA
Heptane
Δλ / nm
Fresh
Oxidized
Dodecyl
Methyl
Silane
Acetylated
Fresh
Oxidized
Acetylene
Relative Humidity %

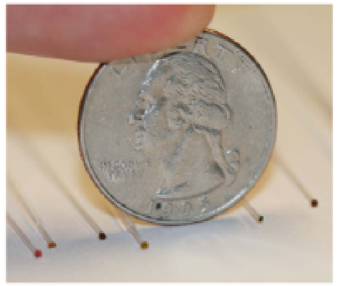

San Diego
Developing Low Power Back-ends
SHARP Dust Sensor
Model GP2Y1010AU
Infrared LED
Photodiode


San Diego
Low Power Sensor Boards
Porous Si Film
LED
Photodiode
Porous Si Chip
LED
Photodiode
Photodiode
pSi
LED


San Diego
Fiber Optic Integration with LED / Photodiode
• Amplification circuitry
• Better signal processing
• Back-biased photodiode for optimal response linearity
Board development by Travis Wong, UCSD Sailor Lab / Ellintrix

Summary

- Flexible, small sized fiber optic sensors for gases and vapors
- Can target classes of vapors
- Low-power, low cost, back-end that can be considerably miniaturized



Acknowledgements

Collaborators

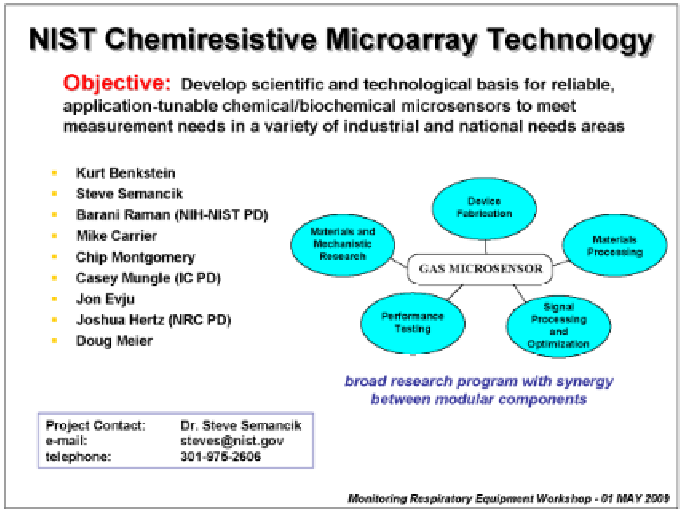
Dr. Michael J. Sailor (Advisor, UCSD)
Anne Ruminski (UCSD)
Jay L. Snyder (NIOSH / NPPTL)

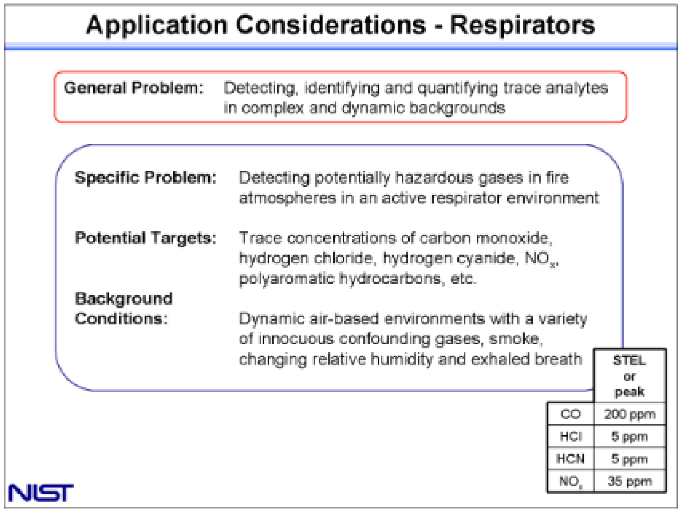
Support

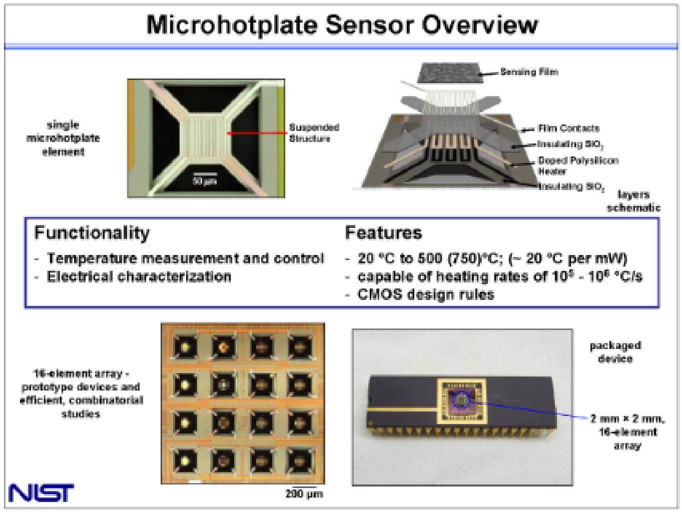
National Science Foundation,
Grant No. DMR-0806859

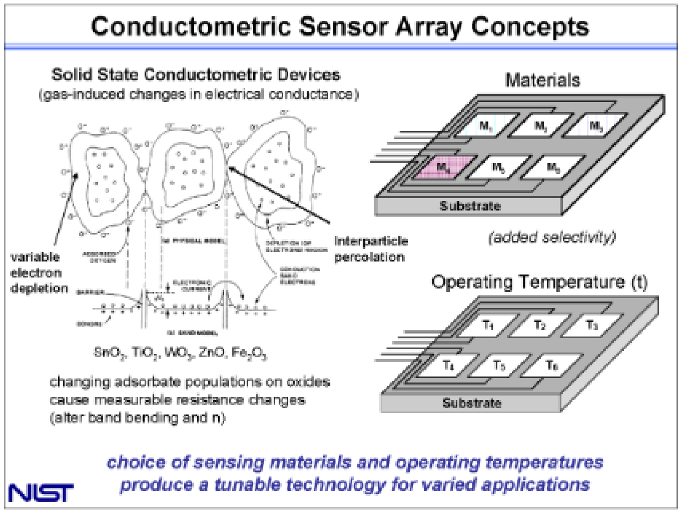
US Army Small Business
Technology Transfer (STTR)
Program award to Elintrix, inc.

Appendix F NIST Chemiresistive Microarray Technology – Kurt Benkstein (NIST)





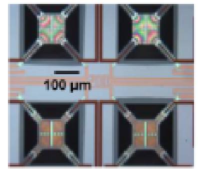




Film Deposition and Processing Methods

Local Heating

- Thermally activated CVD
- Sol-gel, suspension drying
- Annealing
- Thermal lithography
- Thermally assisted imprinting

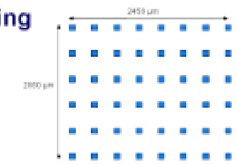


Local Potential Control

- Electrochemical deposition
- (Di-)Electrophoretic deposition/ alignment

Micro-Dispensing (pipetting)

Masking

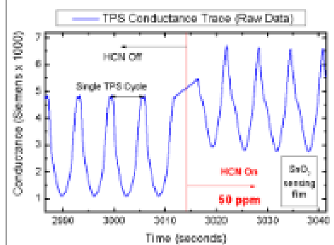


litho-defined shadow mask

all processing done after etching and packaging (to avoid etchants and to use electrical contacts)

NIST

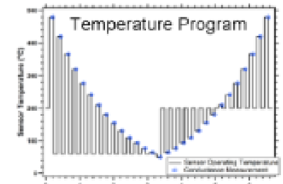
Temperature-Programmed Sensing



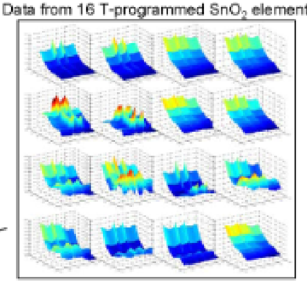
Data from 1 T-programmed SnO_2 element

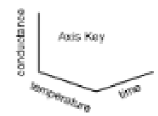
Repeated 7 s cycles of 2-section program

HCN changes response signature



Data from 16 T-programmed SnO_2 elements





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Signal Processing Methods

Dimensionality Reduction and Data Preprocessing

Principal component analysis (PCA)
Linear discriminant analysis (LDA)
Baseline correction

Recognition Classifiers

Artificial Neural Network (ANN)
K-nearest neighbors

	Generation	Training	Signal Processing
crawling	1	off-line	within-sector
	2	off-line	separate-sector
	3	pre-trained	drift compensation, real time recognition (one material, one target)
running	4	pre-trained	multi-materials and real time discrimination of multiple targets

NIST

Case Study in Related Application Area

DHS-Supported Study on Detection of Trace Hazards in Realistic/Varied Backgrounds

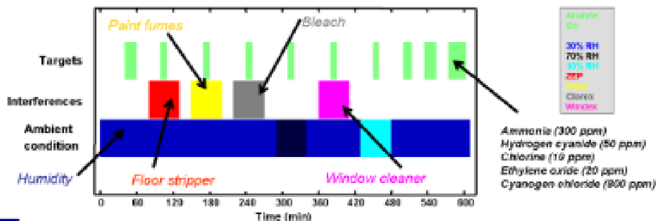
NIST

Challenging Sensing Problem: DHS Test Matrix

high-priority toxic industrial chemicals (TICs)

Calibrated analytes	Abbreviation	Vapor pressure (20 °C)	IDLH concentration
Ammonia	NH	891 k Pa	300 µmol/mol
Hydrogen cyanide	HCN	82.3 k Pa	50 µmol/mol
Chlorine	CL	638 k Pa	10 µmol/mol
Cyanogen chloride	CK	133 k Pa	20 µmol/mol
Ethylene oxide	EO	146 k Pa	800µmol/mol

experimental sequence



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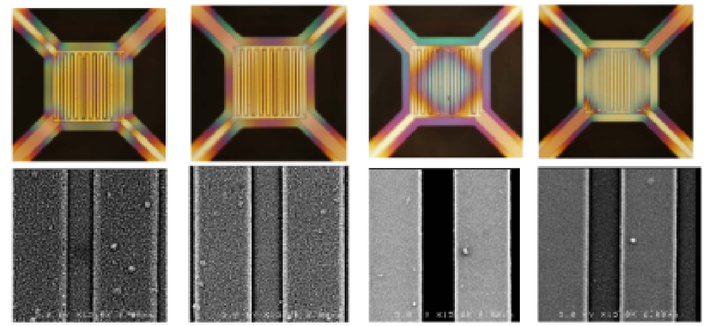
Robust Oxide Films for Chemical Sensing

films fabricated via self-lithographic chemical vapor deposition (CVD)
[optical (top) and scanning electron microscope (SEM, bottom) images shown]



SnO_2 sensing film | TiO_2/SnO_2 layered sensing film | TiO_2 sensing film | Ru-doped TiO_2 sensing film

similar semiconducting oxide films used for TICs, CWSs, CWAs, VOCs

NIST

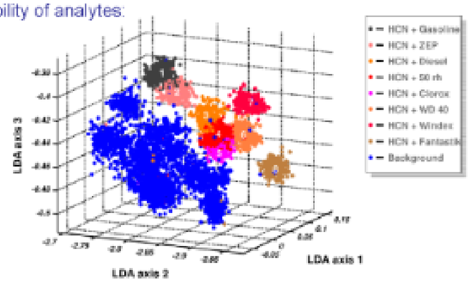
Richness of Data

Is there sufficient information from these sensors to tackle the challenges:

- Detect and discriminate between a variety of target species
- Do so with the targets at trace concentration levels (parts per million and below)
- Ignore changes in background caused by fluctuating humidity levels, changing innocuous species (interferents)

Linear Discriminant Analyses (LDA) applied to data demonstrate separability of analytes:

50 ppm HCN (IDLH)



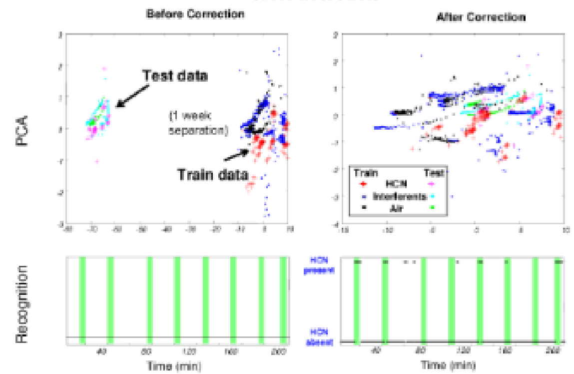
NIST

LDA seeks to maximize the separation between two conditions, while minimizing the variance within each condition

Data Preprocessing to Improve Detection

Example: drift can be a significant problem

HCN detection



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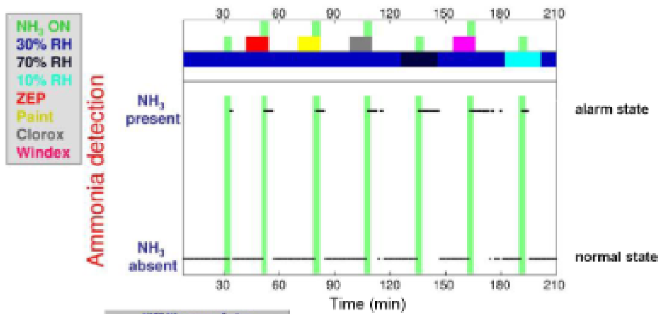
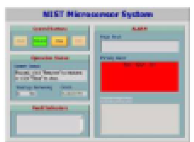
offset correction - demonstrated off-line

Pre-Trained, "Real-Time" Detection of Ammonia

Extension to Real-Time Detection





Red
NH present

on-line result 1 month after training

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Key Research Areas

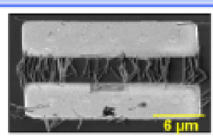
DHS case study demonstrates tunability of the microsensor to a specific problem -- additional research is needed to enhance performance and extend capabilities to other application areas

- **High-performance nanomaterials**
- **Adaptive operational protocols and new signal processing approaches**
- **Tests against challenging new application areas**

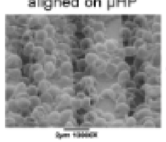
➢ Fundamental studies and concepts to enhance microsensor performance through realization of advanced artificial olfaction

NIST

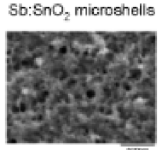
High-Performance Materials



SnO_x nw: aligned on µHP



$Sb:SnO_2$ microshells

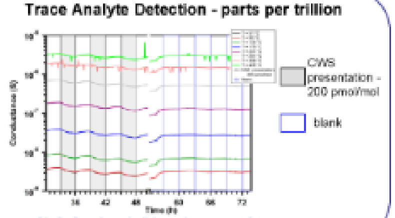


spongy PANI/nafion

Modular addition of nanostructured materials to the microsensor array can provide enhanced performance:

- Shorter response times
- Lower limits of detection
- Longer stability

Trace Analyte Detection - parts per trillion



$Sb:SnO_2$ microshell-based sensor at 8 temperatures

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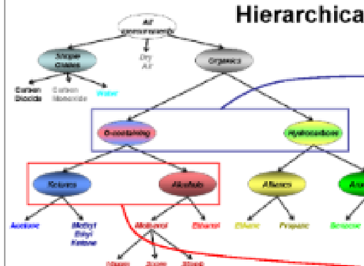
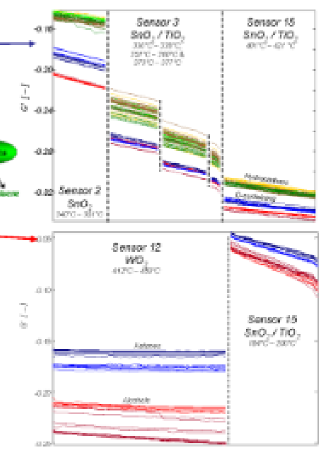
New Signal Processing Approaches - Bio-inspired

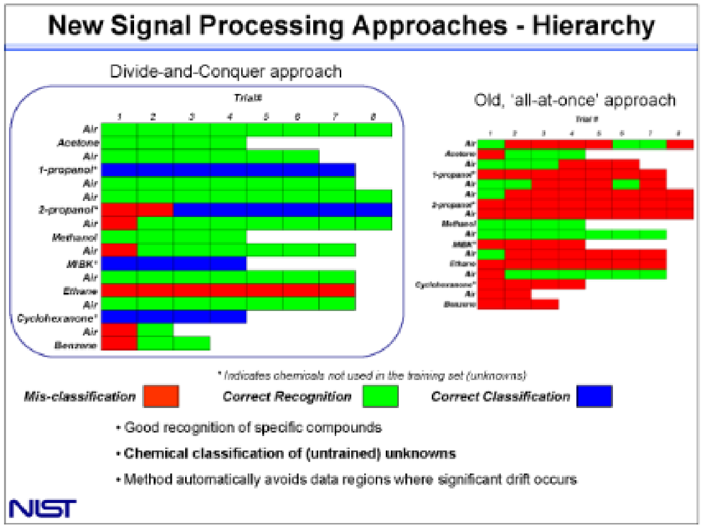
Hierarchical Approach

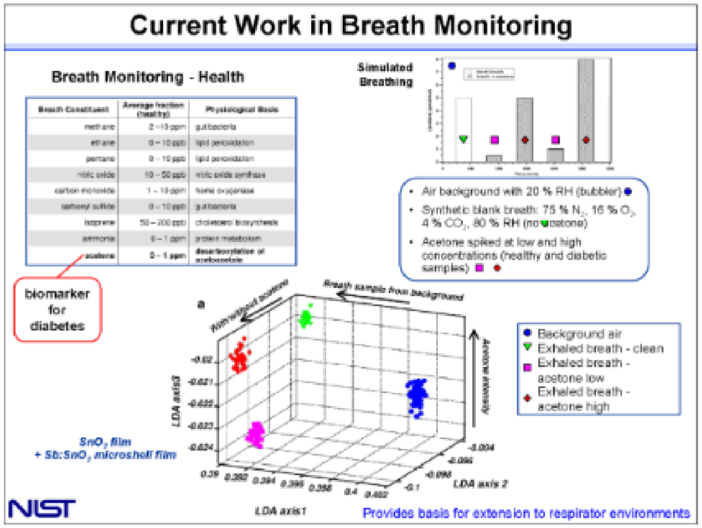


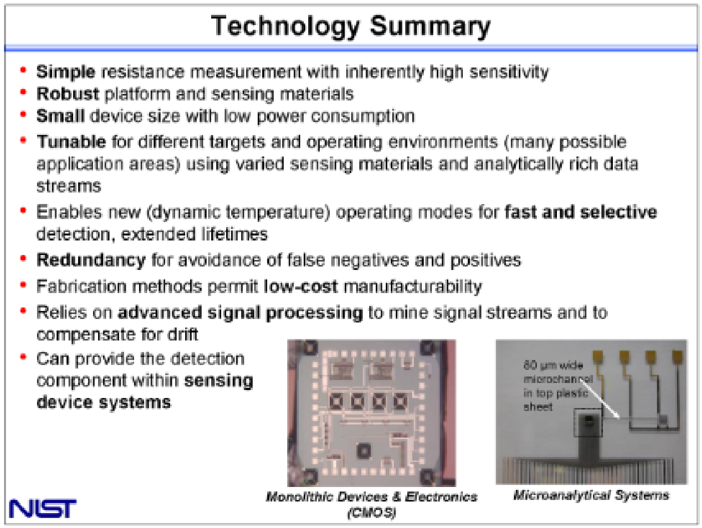


- Ask increasingly precise questions about chemical identity
- Employ (different) optimized regions from the measured T-dependent training set to address each successive recognition/classification problem

NIST


New Signal Processing Approaches - Hierarchy
Divide-and-Conquer approach
Trial#
Air
Acetone
1-propanol*
2-propanol*
Methanol
MIBK*
Ethane
Cyclohexanone*
Benzene
Old, 'all-at-once' approach
* Indicates chemicals not used in the training set (unknowns)
Mis-classification
Correct Recognition
Correct Classification
• Good recognition of specific compounds
• Chemical classification of (untrained) unknowns
• Method automatically avoids data regions where significant drift occurs
NIST


Current Work in Breath Monitoring
Breath Monitoring - Health
Simulated Breathing
• Air background with 20 % RH (bubbler)
• Synthetic blank breath: 75 % N2, 16 % O2, 4 % CO2, 80 % RH (no acetone)
• Acetone spiked at low and high concentrations (healthy and diabetic samples)
biomarker for diabetes
Breath sample from background
With added acetone
Acetone intensity
LDA axis3
LDA axis 2
LDA axis1
Background air
Exhaled breath - clean
Exhaled breath - acetone low
Exhaled breath - acetone high
SnO2 film + Sb:SnO2 microshell film
NIST
Provides basis for extension to respirator environments


Technology Summary
• Simple resistance measurement with inherently high sensitivity
• Robust platform and sensing materials
• Small device size with low power consumption
• Tunable for different targets and operating environments (many possible application areas) using varied sensing materials and analytically rich data streams
• Enables new (dynamic temperature) operating modes for fast and selective detection, extended lifetimes
• Redundancy for avoidance of false negatives and positives
• Fabrication methods permit low-cost manufacturability
• Relies on advanced signal processing to mine signal streams and to compensate for drift
• Can provide the detection component within sensing device systems
80 µm wide microchannel in top plastic sheet
Monolithic Devices & Electronics (CMOS)
Microanalytical Systems
NIST

Appendix G MEMS Sensor Development for End-of-Service-Life Indicators – Nathan Lazarus (Carnegie Mellon University)

MEMS Sensor Development for End-of-Service-Life Indicators (ESLI)

Nathan Lazarus
Advisor: Gary Fedder
Electrical and Computer Engineering
Carnegie Mellon University, Pittsburgh, PA
nlazarus@cmu.edu

1

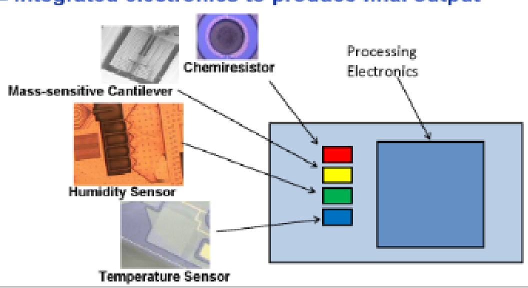
ESLI Sensor Requirements

- Low cost
- Sensitive to a range of contaminants
- Stable
  - Long shelf life
  - Insensitive to temperature and humidity
- Difficult to meet with a single sensor

2

Integrated Sensor Array

- Array of sensors
  - Separate sensors for temperature, humidity and chemicals of interest
- Integrated electronics to produce final output

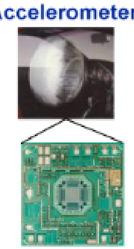


3

MEMS

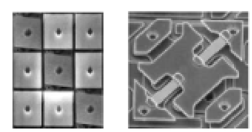
- Microelectromechanical systems
  - Miniaturized mechanical structures
  - Emerging technology

Accelerometers



Analog Devices

Projection systems

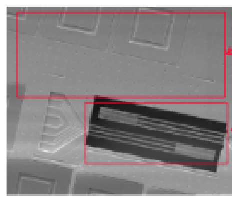


Digital Micromirror Device with 848 x 600 mirrors – SVGA
(WWW.DLP.COM)

4

Fabrication

- Metal layers of standard semiconductor process used to make mechanical structures
  - Allows mechanical structures to be integrated directly with electronics



Protected area for electronics

Mechanical structures

5

Inkjet Deposition

- Custom inkjet system used to deposit sensitive polymer in solution
  - Allows targeted deposition of material with micron-scale targeting accuracy

Piezoelectric jet

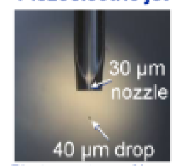
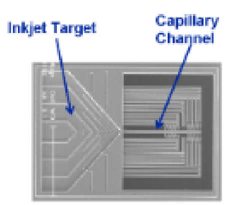


Photo courtesy of Lee Weiss & Larry Schultz

6

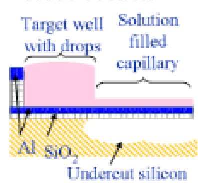
Polymer Wicking

- Polymer deposited in solution in a fixed inkjet target
- Capillary forces pull material into fragile MEMS structure



Micro-capillary cantilever

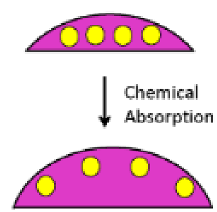
Cross section

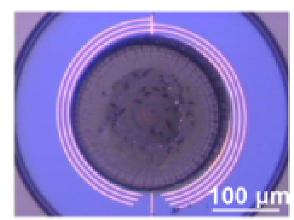


7

Gold Nanoparticle Chemiresistors

- Conductive gold cores coated in non-conductive polymer
  - Distance changes between gold cores upon chemical absorption results in changes in resistance.

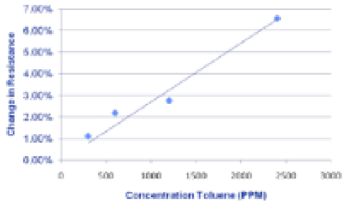


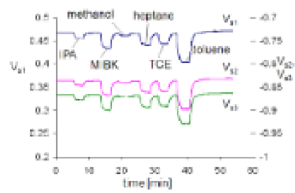


8

Chemresistor Results

- Output measured using a voltage divider circuit
  - Subtracts away output of a capped reference sensor
- Sensitive to volatile organic compounds such as toluene





G. Fedder et al., *IMCS 2008*

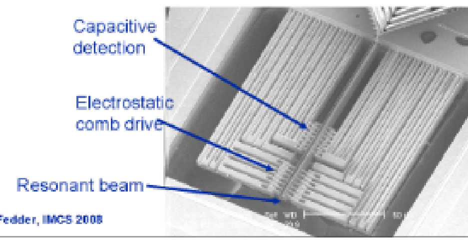
Cantilever Gravimetric Sensor

- Changing mass of a beam used to measure chemical absorption
- Mass measured by changing resonant frequency of the beam

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m_{eff}}}$$

m_{eff} = mass

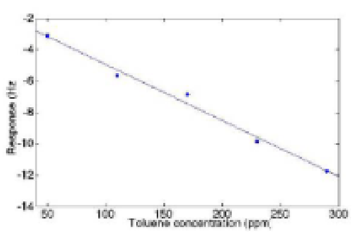
k_{eff} = spring constant



S. Bedair and G. Fedder, IMCS 2008

Gravimetric Sensor Results

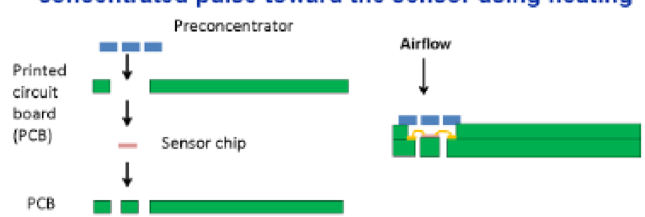
- PBMA loaded microgroove design ~ 680 pg
  - Measured mass sensitivity -20.3 fg/Hz
  - 205.8 kHz oscillation frequency
- Calculated concentration sensitivity is -0.04 Hz/ppm



Vapor	Concentration sensitivity (Hz/ppm)
Toluene	-0.037
Benzene	-0.015
Acetone	-0.0019

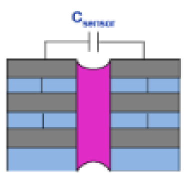
Preconcentration

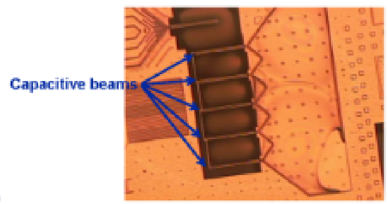
- Recommended exposure limits can be in parts per billion range
  - Difficult to measure for most types of chemical sensor
- Chemical can be absorbed then released in a concentrated pulse toward the sensor using heating



Capacitive Humidity Sensor

- Sensing changes in dielectric constant
  - Water vapor: $\varepsilon_r = 78$
  - Most polymers: $\varepsilon_r = \sim 3 - 4$
- Large capacitance change upon absorption of water vapor





N. Lazarus and G. Fedder, *Proc. of IEEE MEMS 2009*

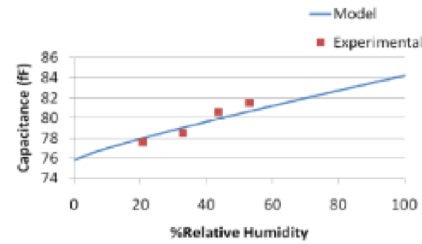
13

Sensitive Polymer

- Polyimide
  - Commonly used in humidity sensing
  - Linear response*

$$\varepsilon = \left\{ \gamma\left(\varepsilon_{H2O}^{1/3} - \varepsilon_{PI}^{1/3}\right) + \varepsilon_{PI}^{1/3} \right\}^3$$

γ is volume fraction of water vapor, ε_{PI} ε_{H2O} are dielectric constants of polyimide and water

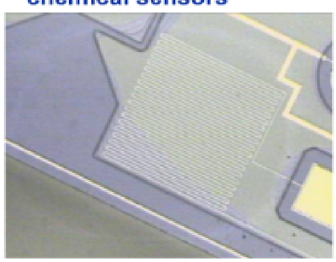


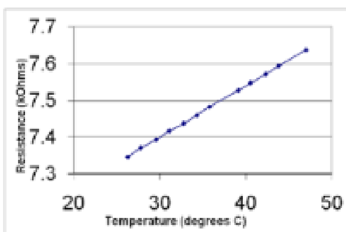
*H. Shibata, M. Ito, M. Asakura, and K. Watanabe, *Proc. of IEEE IMTC 1996*

14

Temperature Sensing

- Some metals have resistances that vary linearly with temperature
  - Used as a temperature sensor
- Allows compensation for thermal variations in chemical sensors





15

Conclusions

- Sensors for measuring various chemicals as well as temperature and humidity have been developed
  - Intended for use in ESLI systems
- Use of multiple sensor system allows compensation for thermal and humidity responses and differentiation between chemicals.
- Future development aimed at designing a broader system incorporating all of these sensors.

16

Acknowledgements

- Collaborators:

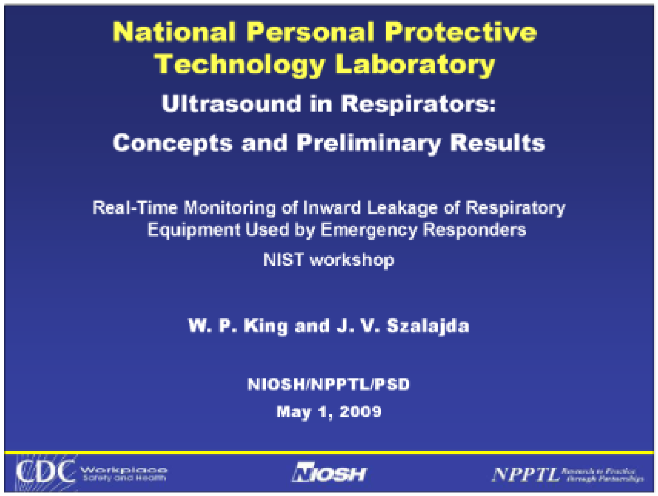
  CMU: G. Fedder, S. Bedair, K. Dorsey, K. Frank, N. Garg, R. Jin, D. Lambeth, S. Santhanam, L. Schultz, L. Weiss, J. Wu

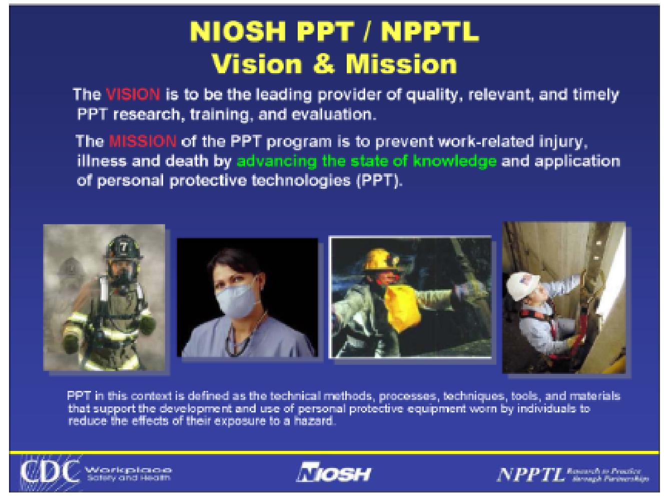
  NIOSH: J. Snyder, T. Rozzi, J. Greenblatt, D. Barkand

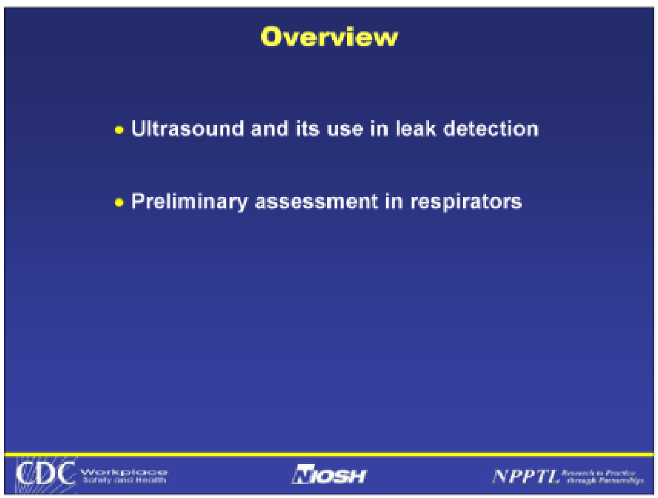
- Research funded by the NIOSH National Personal Protective Technology Laboratory (NPPTL) and the Air Force Office of Scientific Research (AFOSR)

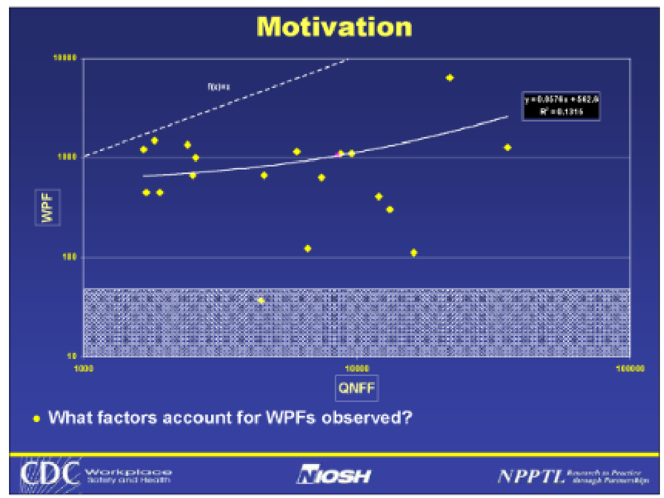
17

Appendix H Ultrasound in Respirators: Concepts and Preliminary Results – William King and Jonathan Szalajda (NIOSH/NPPTL)









Useful Tool Needed

- Method of monitoring fit or leakage *in situ*
  - Actual respirator
  - Real time

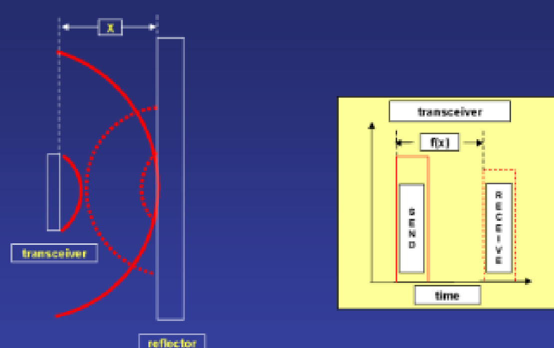
Ultrasound

- Cyclic sound pressure with a frequency greater than the upper limit of human hearing (≥ 20 kilohertz)

- Airborne ultrasound technology applications:
  - SONAR, Tracking and positioning
  - Leak detection
- Exposure to airborne ultrasound does not appear to pose a human health risk
  - Inaudible

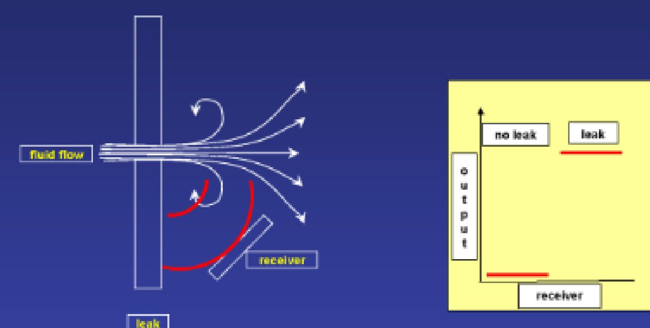
TLVs for Ultrasound (2008)		
Mid-Frequency of Third-Octave Band (kHz)	One-third Octave-Band Level in Air in dB	
	Ceiling Values	8-Hour TWA
12.5	105	88
16	105	92
20	105	94
25	110	—
31.5	110	—
40	110	—
50	110	—
80	110	—

Ultrasonic Ranging



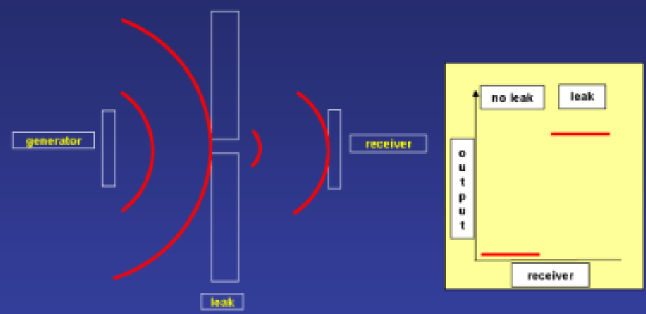
Transit time of ultrasound radiation is directly related to distance, X

Leak Detection



Turbulent flow from leaks generates ultrasound radiation

Leak Detection with Generator



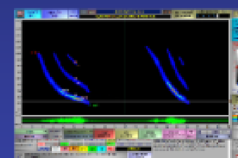
Leakage detection with generated ultrasound radiation

Ultrasound Technology

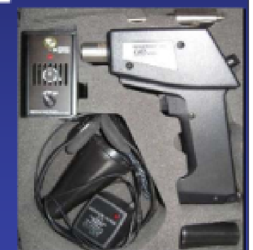
- Salient aspects
  - Low power and size
  - Low cost
  - Sound techniques applicable

Ranging device

0.4" dia. x 0.1"



Frequency analysis



Leak detector with source

Questions for use in respirators

- Ultrasound sources
  - Leaks
  - Respiration
  - Others
- Assessment of information available from ultrasound
  - Magnitude
    - Correlation with leak and fit factor
  - Temporal
  - Spatial
  - Spectral

Respirator Source Assessment

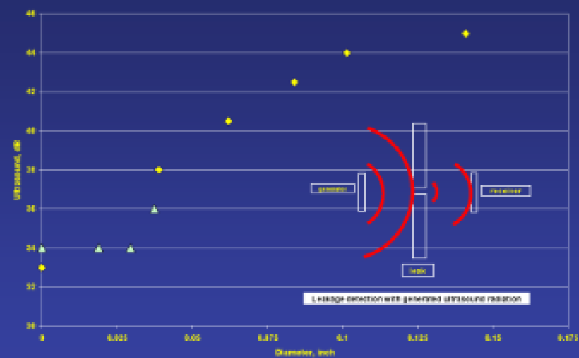
- Reynolds numbers for some sources

Source	Re	V_s	D	ν	μ	ρ	Ve	PF	W
		m s⁻¹	m	m² s⁻¹	N s m⁻² or Pa·s	kg m⁻³	L·min.⁻¹		m
leak	2.4E+01	3.3	0.0001	1.37E-05	0.0000178	1.294643	20	100	0.01
nostril	3.4E+09	259.8	0.007	1.37E-05	0.0000178	1.294643	10		
mouth	8.2E+02	26.7	0.023	1.37E-05	0.0000178	1.294643	20		

  - Critical Reynolds number (Re) 10^3 - 10^4
    - Turbulent flow expected above critical Reynolds number

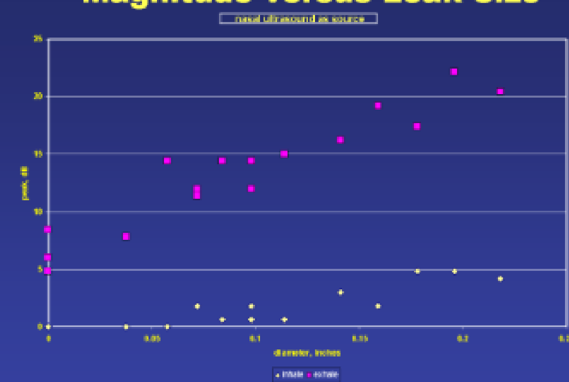
- Nasal breathing is the only expected source of ultrasound

Magnitude versus Leak Size



Adjusted $R^2 = 0.91$

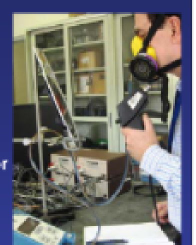
Magnitude versus Leak Size



Adjusted $R^2 = 0.90$ exhale, 0.75 inhale

Preliminary Evaluation of Fit/Leak with Half-masks

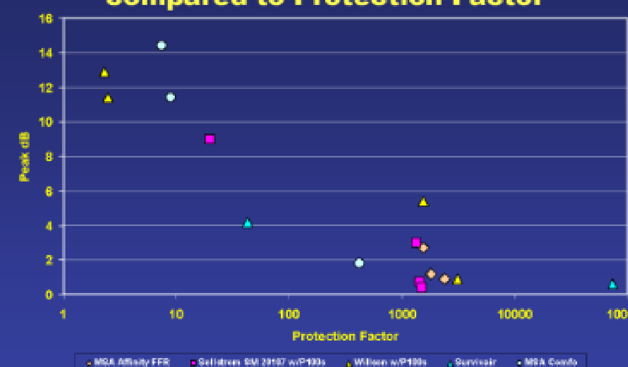
- Probed respirators to simultaneously measure fit factor with PortaCount
- Used nasal breathing as source on single subject
- Measured ultrasound levels at five points around face seal
  - Single exercise/sampling period
- On replicates changed strap tension to modulate fit factor



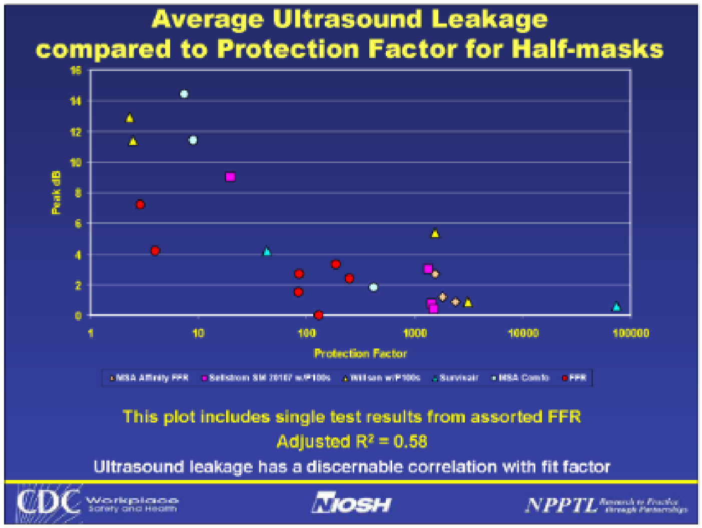
Representative Data Collected

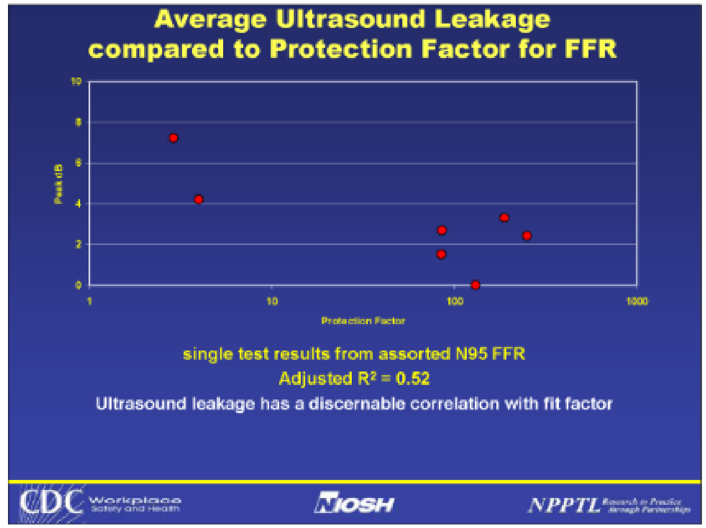
Respirator	Condition	Peak ultrasound, dB				Fit factor
		point	inhale	exhale	bgd.	
MSA Aff.	loose	left cheek	0	3	0	1500
		chin	3	9	0	
		right cheek	0	6	0	
		right nose	0	3	0	
		left nose	0	3	0	

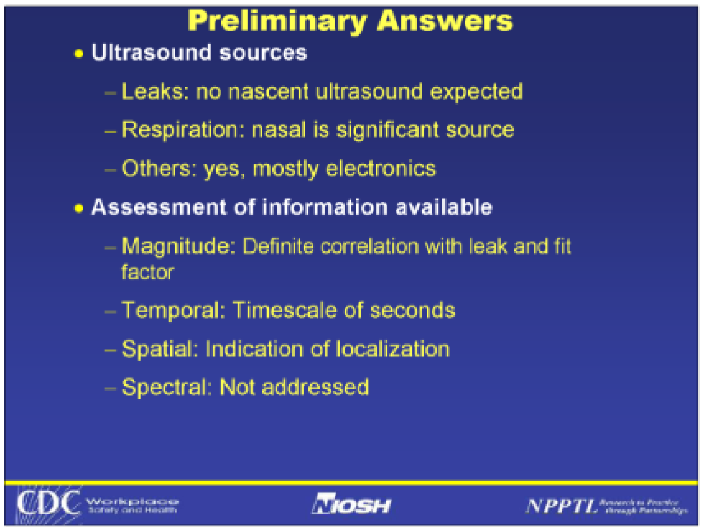
Average Ultrasound Leakage compared to Protection Factor



Adjusted $R^2 = 0.79$

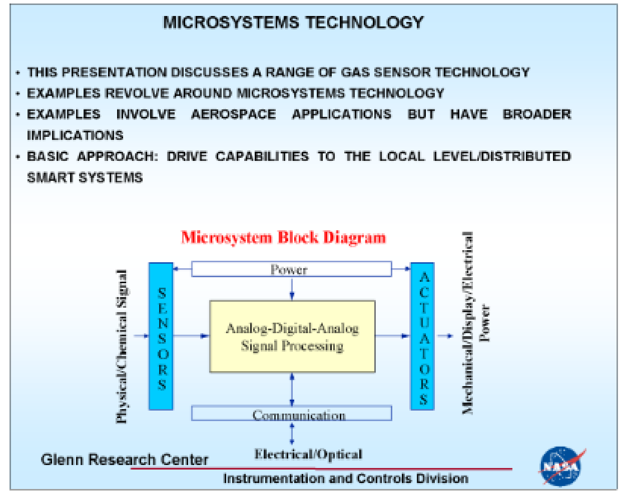

Average Ultrasound Leakage
compared to Protection Factor for Half-masks
Peak dB
Protection Factor
MSA Affinity FFR
Survivair
MSA Comfo
FFR
This plot includes single test results from assorted FFR
Adjusted R² = 0.58
Ultrasound leakage has a discernable correlation with fit factor
CDC Workplace Safety and Health
NIOSH
NPPTL

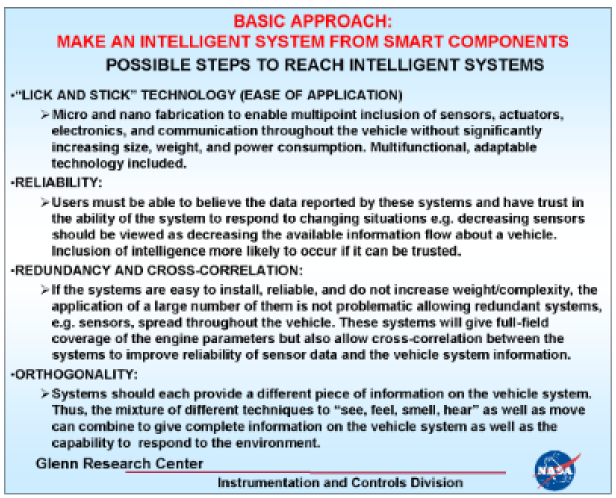

Average Ultrasound Leakage
compared to Protection Factor for FFR
Peak dB
Protection Factor
single test results from assorted N95 FFR
Adjusted R² = 0.52
Ultrasound leakage has a discernable correlation with fit factor
CDC Workplace Safety and Health
NIOSH
NPPTL

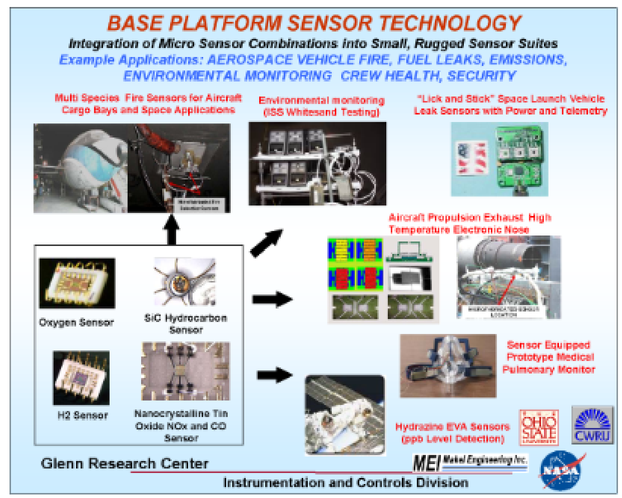

Preliminary Answers
• Ultrasound sources
– Leaks: no nascent ultrasound expected
– Respiration: nasal is significant source
– Others: yes, mostly electronics
• Assessment of information available
– Magnitude: Definite correlation with leak and fit factor
– Temporal: Timescale of seconds
– Spatial: Indication of localization
– Spectral: Not addressed
CDC Workplace Safety and Health
NIOSH
NPPTL


Quality Partnerships Enhance Worker Safety & Health
Visit Us at: www.cdc.gov/niosh/npptl
Disclaimer:
The findings and conclusions in this presentation have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy.
Thank you
CDC Workplace Safety and Health
NIOSH
NPPTL

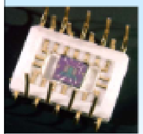
Appendix I Chemical Sensors for Aerospace Applications: From Sensor Platforms to System Application – Gary Hunter (NASA Glenn Research Center)







HYDROGEN LEAK SENSOR TECHNOLOGY



- STATUS: OPERATIONAL SYSTEM ON ISS WITH ASSOCIATED HARDWARE
- BEING PREPARED FOR CLV IMPLEMENTATION

1995 R&D 100 AWARD WINNER

NASA 2003 TURNING GOALS INTO REALITY SAFETY AWARD

Shuttle X33 X43 Helios ISS

Aft Compartment Hydrogen Monitoring | Hydrogen Safety Monitoring | Hydrogen Safety Monitoring | Fuel Cell Safety and Process Monitoring | Life Support Process and Safety Monitoring

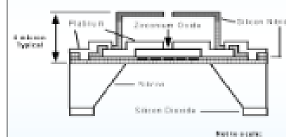
Glenn Research Center MEI Makel Engineering Inc. CWRU

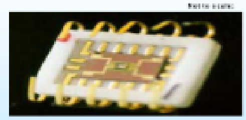
Instrumentation and Controls Division

MICROFABRICATED OXYGEN SENSOR TECHNOLOGY

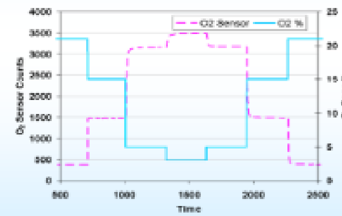
CWRU

- MICROFABRICATED AND MICROMACHINED FOR MINIMAL SIZE, WEIGHT AND POWER CONSUMPTION (NEAR 100 mW FOR ~500 C OPERATION)
- AMPEROMETRIC OPERATION ALLOWS MEASUREMENT OF OXYGEN OVER A WIDE CONCENTRATION RANGE (0-100%)
- CHAMBER STRUCTURE CONTROLS OXYGEN DIFFUSION RATE
- RELATIVELY MATURE TECHNOLOGY/PACKAGING COULD BE IMPROVED TO DECREASE POWER CONSUMPTION





ZrO2 Oxygen Sensor



Zirconia Based Oxygen Microsensor Response To Various Oxygen Concentrations

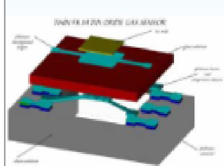
Glenn Research Center

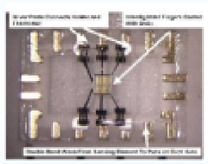
Instrumentation and Controls Division

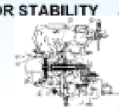
MICROFABRICATED TIN OXIDE BASED NOx AND CO SENSOR TECHNOLOGY

CWRU

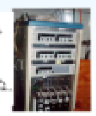
- MICROFABRICATED FOR MINIMAL SIZE, WEIGHT AND POWER CONSUMPTION
- MICROMACHINED TO MINIMIZE POWER CONSUMPTION AND IMPROVE RESPONSE TIME
- TEMPERATURE DETECTOR AND HEATER INCORPORATED INTO SENSOR STRUCTURE
- NANOFABRICATION OF TIN-OXIDE TO INCREASE SENSOR STABILITY





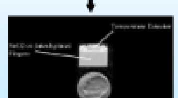


50 Hp Gas Turbine

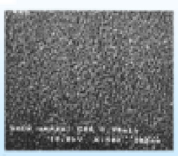


Industry Standard Continuous Emission Monitoring Equipment

REPLACE INSTRUMENT RACK SIZED SYSTEM WITH DIME SIZED SENSOR AND ACCOMPANYING ELECTRONICS



Nanocrystalline Tin Oxide



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SENSOR SYSTEM DEVELOPMENT

- EACH SENSOR PLATFORM PROVIDES QUALITATIVELY VERY DIFFERENT TYPES OF INFORMATION ON THE ENVIRONMENT
- SENSOR ARRAY VARIES WITH APPLICATION
  - MICROFABRICATION TECHNIQUES MANDATORY/FUNDAMENTAL TO THE APPROACH
- BASIS CHEMICAL SENSOR FEATURES:
  - RESPONSE TIME, SENSITIVITY, SELECTIVITY, STABILITY
  - BATCH FABRICATION, PROCESSING REPRODUCIBILITY, CONTROL OF STRUCTURE
  - TAILOR SENSOR SYSTEM FOR THE APPLICATION
- SUPPORTING TECHNOLOGIES NECESSARY
  - PACKAGING (OFTEN UP TO 70% OF OVERALL SENSOR COST)
  - SIGNAL CONDITIONING AND PROCESSING
  - SOFTWARE (E.G. NEURAL NET PROCESSING, MODELING)
  - POWER AND COMMUNICATION

See for example: G. W. Hunter, C.C. Liu, D. Makel, Microfabricated Chemical Sensors For Aerospace Applications, MEMS Handbook Second edn, Design and Fabrication, CRC 2006, Press LLC, Boca Raton, Ch. 11.

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CHEMICAL SENSOR APPLICATION DEVELOPMENT AREAS

SAFETY

LEAK DETECTION

DETECTION OF FUEL AND OXYGEN LEAKS FOR SPACE TRANSPORTATION APPLICATIONS SUCH AS SPACE SHUTTLE, CREW LAUNCH VEHICLE, AND EXPLORATION MISSIONS. WIDE RANGE DETECTION IN INERT ENVIRONMENTS AND POSSIBLY CRYOGENIC CONDITIONS.

FIRE DETECTION

DETECTION OF FIRE PRECURSORS (E.G. CO AND CO2) IN CARGOBAY APPLICATIONS TO SUPPLEMENT EXISTING TECHNOLOGY. CHEMICAL SIGNATURE IN THE PRESENCE OF A NUMBER OF INTERFERING GASES. COMPLEMENT EXISTING SMOKE DETECTION SYSTEMS.

EMISSIONS

DETECTION OF HYDROCARBONS, NOx, CO, HYDROGEN, ETC. FOR HEALTH MONITORING AND ACTIVE COMBUSTION CONTROL APPLICATIONS. SENSITIVE DETECTION IN HIGH TEMPERATURE HARSH ENVIRONMENTS IN THE PRESENCE OF A NUMBER OF INTERFERING GASES.

ENVIRONMENTAL MONITORING/BIO/SECURITY

DETECTION OF HYDRAZINE FOR ISS/EVA APPLICATIONS

ENVIRONMENTAL MONITORING FOR ISS APPLICATIONS

BREATH MONITORING FOR HUMAN HEALTH

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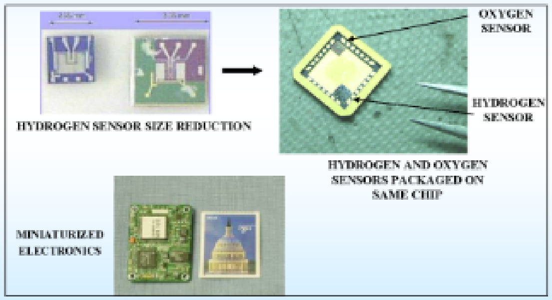
"LICK AND STICK" LEAK SENSOR SYSTEM

- COMBINE FUEL (HYDROGEN, HYDROCARBON) WITH OXYGEN IN AN ARRAY: DETERMINE EXPLOSIVE COMBINATIONS
- SELF-CONTAINED SYSTEM WHICH CAN BE IMPLEMENTED WHEREVER, WHENEVER NEEDED WITHOUT REWIRING OR SIGNIFICANT POWER DRAIN TO THE VEHICLE
- ON-GOING ACTIVITY: DECREASE SIZE AND POWER OF SENSORS/ELECTRONICS

FIRST STEP: COMBINE SMALLER SENSORS WITH SMALLER, SMART ELECTRONICS



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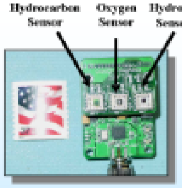
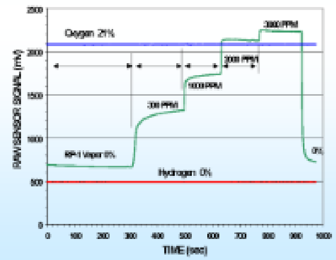
"LICK AND STICK" LEAK SENSOR SYSTEM DEMONSTRATION

- WIRELESS DEMONSTRATION OF 3 SENSOR SYSTEM ACHIEVED
- BASELINE: ZIRCONIA BASED O2 SENSOR (ALTHOUGH NAFION BASED ROOM TEMPERATURE SYSTEM BEING MATURED FOR USE)
- LONGEVITY OF SENSOR SYSTEM LIFE ON A BATTERY IS A LIMITATION IN SOME APPLICATIONS
- MOVE FROM HIGH TEMPERATURE SENSOR TECHNOLOGY TO LOWER TEMPERATURE SENSORS
- BEING QUALIFIED FOR CREW LAUNCH VEHICLE APPLICATIONS (HARDWIRED) FOR HYDROGEN DETECTION ONLY





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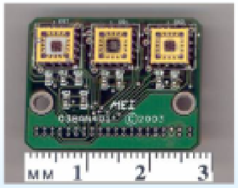
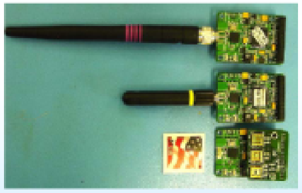
"LICK AND STICK" LEAK SENSOR SYSTEM

- SENSORS, POWER, AND TELEMETRY SELF-CONTAINED IN THE NEAR THE SIZE OF A POSTAGE STAMP
- MICROPROCESSOR INCLUDED/SMART SENSOR SYSTEM
- VERIFY SYSTEM COMPATIBILITY WITH SPACE APPLICATIONS
- ADAPTABLE CORE SYSTEM WHICH CAN BE USED IN A RANGE OF APPLICATIONS
- MULTIPLE CONFIGURATIONS AVAILABLE



"Lick and Stick" Leak Detection Electronics and Three Sensors



System configured with different wireless antennae.

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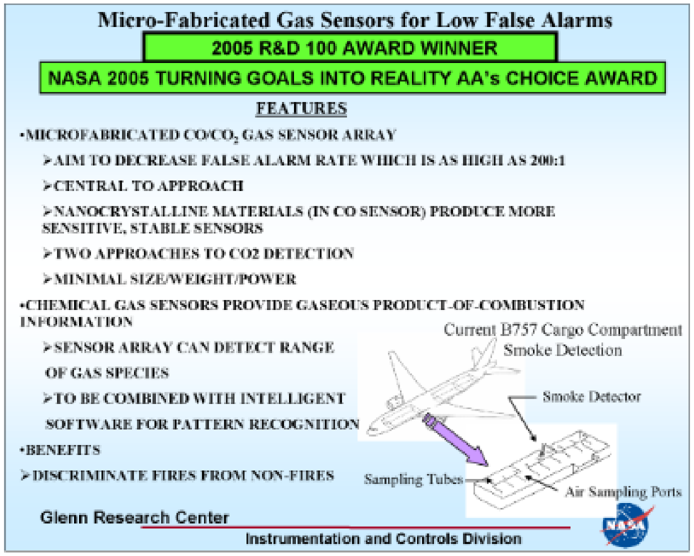

Micro-Fabricated Gas Sensors for Low False Alarms
2005 R&D 100 AWARD WINNER
NASA 2005 TURNING GOALS INTO REALITY AA's CHOICE AWARD
FEATURES
•MICROFABRICATED CO/CO_2 GAS SENSOR ARRAY
➢AIM TO DECREASE FALSE ALARM RATE WHICH IS AS HIGH AS 200:1
➢CENTRAL TO APPROACH
➢NANOCRYSTALLINE MATERIALS (IN CO SENSOR) PRODUCE MORE SENSITIVE, STABLE SENSORS
➢TWO APPROACHES TO CO2 DETECTION
➢MINIMAL SIZE/WEIGHT/POWER
•CHEMICAL GAS SENSORS PROVIDE GASEOUS PRODUCT-OF-COMBUSTION INFORMATION
➢SENSOR ARRAY CAN DETECT RANGE OF GAS SPECIES
➢TO BE COMBINED WITH INTELLIGENT SOFTWARE FOR PATTERN RECOGNITION
•BENEFITS
➢DISCRIMINATE FIRES FROM NON-FIRES
Current B757 Cargo Compartment Smoke Detection
Smoke Detector
Sampling Tubes
Air Sampling Ports
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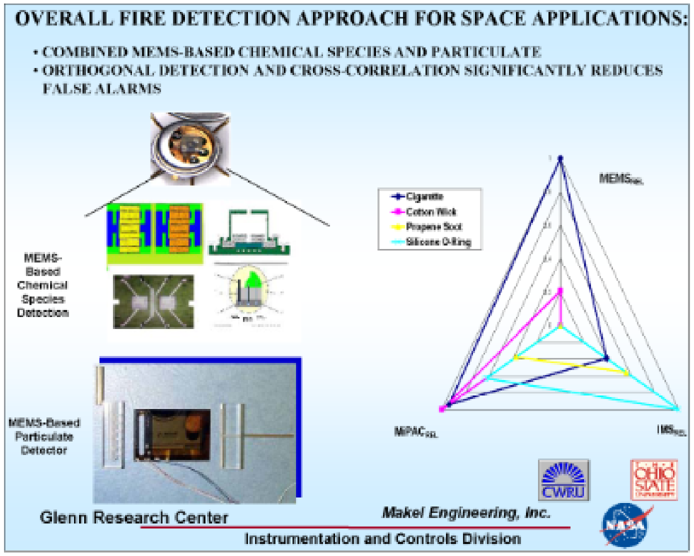
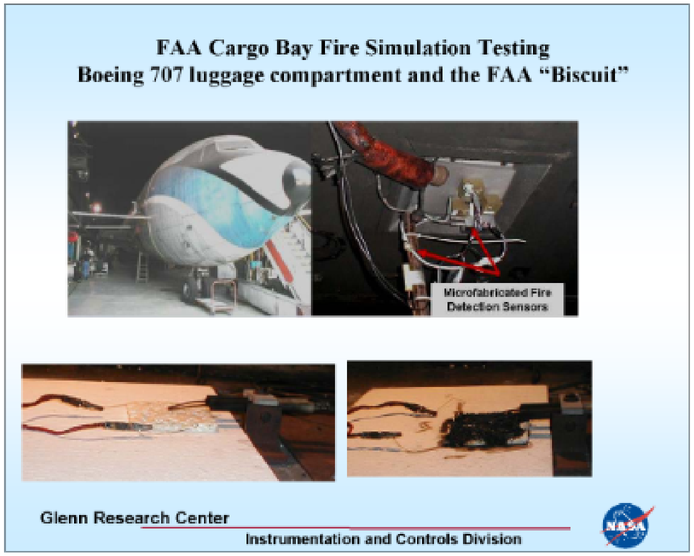


OVERALL FIRE DETECTION APPROACH FOR SPACE APPLICATIONS:
• COMBINED MEMS-BASED CHEMICAL SPECIES AND PARTICULATE
• ORTHOGONAL DETECTION AND CROSS-CORRELATION SIGNIFICANTLY REDUCES FALSE ALARMS
MEMS-Based Chemical Species Detection
MEMS-Based Particulate Detector
Cigarette
Cotton Wick
Propene Soot
Silicone O-Ring
CWRU
OHIO STATE
Makel Engineering, Inc.
Glenn Research Center
Instrumentation and Controls Division



FAA Cargo Bay Fire Simulation Testing
Boeing 707 luggage compartment and the FAA "Biscuit"
Microfabricated Fire Detection Sensors
Glenn Research Center
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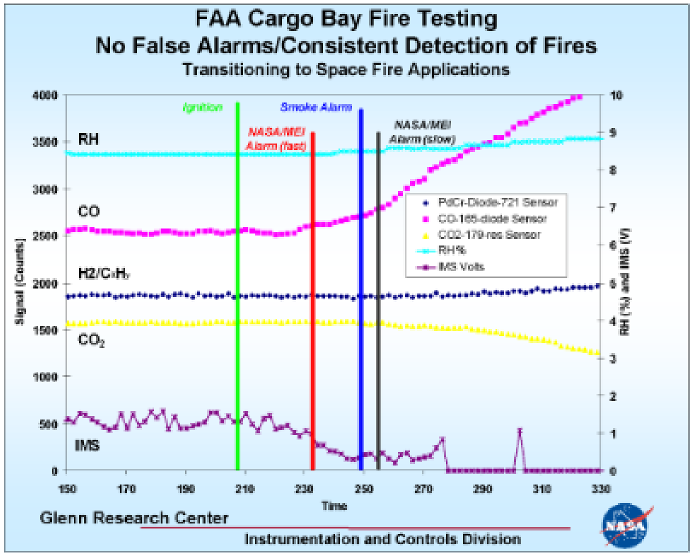

FAA Cargo Bay Fire Testing
No False Alarms/Consistent Detection of Fires
Transitioning to Space Fire Applications
Ignition
Smoke Alarm
NASA/MEI Alarm (fast)
NASA/MEI Alarm (slow)
RH
CO
H2/CxHy
CO_2
IMS
PdCr-Diode-721 Sensor
CO-165-diode Sensor
CO2-179-res Sensor
RH%
IMS Volts
Signal (Counts)
RH (%) and IMS (V)
Time
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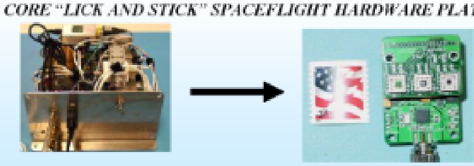
CREW EXPLORATION VEHICLE FIRE DETECTION

- Need for accurate and reliable fire detection; MMFDS aeronautics approach had significant advantages for this application
- Application of this unit for space applications requires modification directly related to the requirements of spaceflight operations
- This includes:
  - Minimization of size, reduction of weight, and reduced power consumption for integration into space flight vehicles
  - Optimization of sensor operating parameters to target likely chemical species and concentration ranges present in space operations
  - Selection of parts and components compatible with space qualified parts listing, i.e., choosing parts which will work in a space radiation and extreme condition environments.

BASIC APPROACH: TRANSITION AERONAUTICS HARDWARE INTO CORE "LICK AND STICK" SPACEFLIGHT HARDWARE PLATFORM



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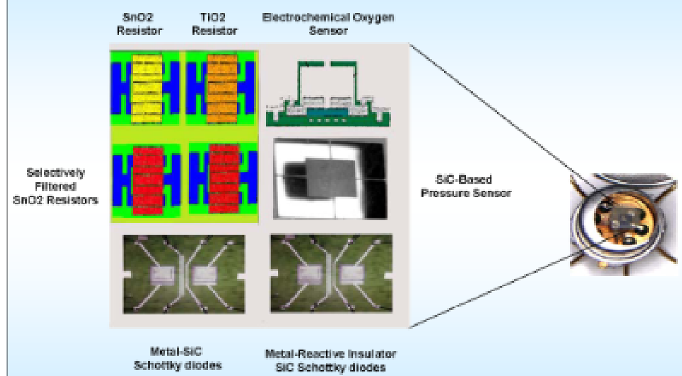
HIGH TEMPERATURE GAS SENSOR ARRAY
HIGH TEMPERATURE ELECTRONIC NOSE



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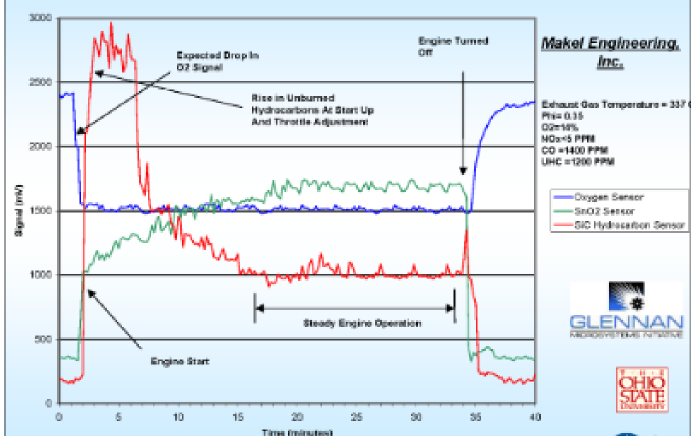
Makel Engineering, Inc. Instrumentation and Controls Division

Harsh Environment Demonstration Testing

1.9 liter, four cylinder HCCI at U.C. Berkeley (propane/air)



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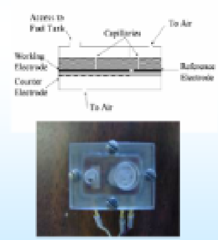
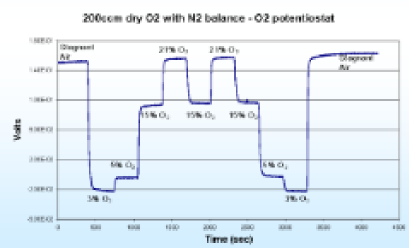
ROOM TEMPERATURE O2 SENSOR TECHNOLOGY

- POSSIBLE REPLACEMENT FOR PRESENT LIQUID ELECTROCHEMICAL CELL TECHNOLOGY
- VIABILITY FOR SPACE BASED APPLICATIONS MUST BE VERIFIED THROUGH AN EXTENSIVE TEST PROGRAM.
- ONE SIGNIFICANT LESSON OF PREVIOUS ISS IMPLEMENTATION IS THAT TESTING IN RELEVANT ENVIRONMENTS OVER THE REQUIRED SENSOR LIFE IS MANDATORY
- FIND THE ISSUES ON THE GROUND OR LAB AND NOT AFTER IT HAS BEEN DEPLOYED ON THE VEHICLE IN SPACE
- TEST TO FAILURE AND ANALYZE THE FAILURE IF POSSIBLE



NAFION O2 Sensor Structure



Preliminary NAFION O2 Sensor Data

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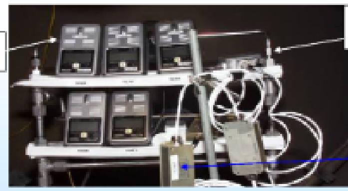
WHITE SANDS TEST FACILITY O2 SENSOR TESTING

- TESTING OCCURRED SIDE BY SIDE WITH EXISTING ISS SENSOR SYSTEMS FOR ISS ENVIRONMENTAL MONITORING AT WHITE SANDS TEST FACILITY
- TESTING OCCURRED OVER A RANGE OF PRESSURES AND O2 CONCENTRATIONS INTEGRATED WITH ELECTRONICS AND PRESSURE COMPENSATION
- REPEATED CYCLES OVER SEVERAL TEST PERIODS APPROXIMATED ~8 YEARS OF ISS OPERATION
- ACCURACY OF CALIBRATION, REPEATABILITY OF DATA, RESPONSE TIME WERE MAJOR OF EVALUATION CRITERIA
  - THIS IS A CRIT 1 (RELATED TO LIFE OF CREW) FUNCTION WITH STRICT CALIBRATION/PERFORMANCE REQUIREMENTS (+/-0.8%)
- MAJOR FINDING: SENSOR FAILURE MECHANISMS IDENTIFIED



NAFION based oxygen sensor (left) and sensors during piggyback testing with NASA CSA-O2 systems

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SENSOR SYSTEM IMPLEMENTATION

- OBJECTIVE: A SELF-AWARE SYSTEM COMPOSED OF SMART COMPONENTS MADE POSSIBLE BY SMART SENSOR SYSTEMS
- SENSOR SYSTEMS ARE NECESSARY AND ARE NOT JUST GOING TO SHOW UP WHEN NEEDED/TECHNOLOGY BEST APPLIED WITH STRONG INTERACTION WITH USER
- SENSORS SYSTEM IMPLEMENTATION OFTEN PROBLEMATIC
  - LEGACY SYSTEMS
  - CUSTOMER ACCEPTANCE
  - LONG-TERM VS SHORT-TERM CONSIDERATIONS
  - SENSORS NEED TO BUY THEIR WAY INTO AN APPLICATION
- SENSOR DIRECTIONS INCLUDE:
  - INCREASE MINIATURIZATION/INTEGRATED INTELLIGENCE
  - MULTIFUNCTIONALITY/MULTIPARAMETER MEASUREMENTS/ORTHOGONALITY
  - INCREASED ADAPTABILITY
  - COMPLETE STAND-ALONE SYSTEMS ("LICK AND STICK" SYSTEMS)
- POSSIBLE LESSONS LEARNED
  - SENSOR SYSTEM NEEDS TO BE TAILORED FOR THE APPLICATION
  - MICROFABRICATION IS NOT JUST MAKING SOMETHING SMALLER
  - ONE SENSOR OR EVEN ONE TYPE OF SENSOR OFTEN WILL NOT SOLVE THE PROBLEM: THE NEED FOR SENSOR ARRAYS
  - SUPPORTING TECHNOLOGIES OFTEN DETERMINE SUCCESS OF A SYSTEM

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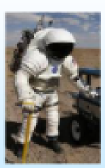
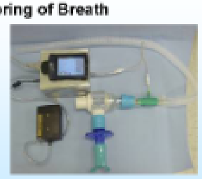
One Potential Vision: "Smart" Suit

- Development of a "Smart" Suit which has self-monitoring, caution and warning, and control capabilities with high levels of reliability, durability, and safety.
- Small, lightweight, low power sensor systems, with increased packaging flexibility, will improve the effectiveness and extensibility of the EVA suits.
- Seamless integration of sensors throughout EVA system improving reliability and capability without significantly increasing system wiring and power.
- Monitor Both Inside And Outside the EVA Suit for Astronaut Health and Safety\Suit Maintenance
  - Inside: For Example, Monitor Suit CO2, O2, Flow to Allow Metabolic Measurements
  - Outside: For Example, Monitor Dust/Toxic Gas/Dangerous Conditions Before Brought Back Into Airlock Or Can Affect Astronaut Safety
- Include Ability to Determine Astronaut Health by Monitoring of Breath

A "Smart" Suit Needs To Monitor Both Internal And External Conditions



Breath Sensor System – includes mouthpiece for breath collection, Nafion drying tube in sample line, sensor manifold with PDA interface, and mini sampling pump



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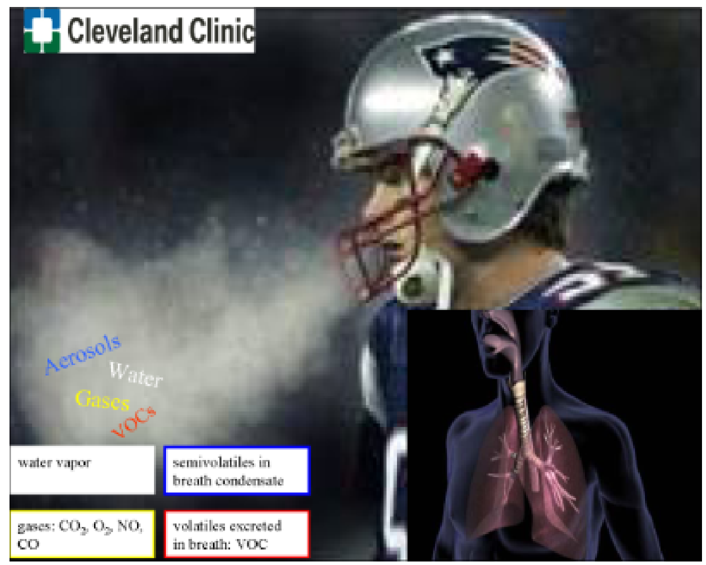
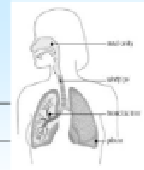


Biomarkers for the diagnosis of disease by breath test



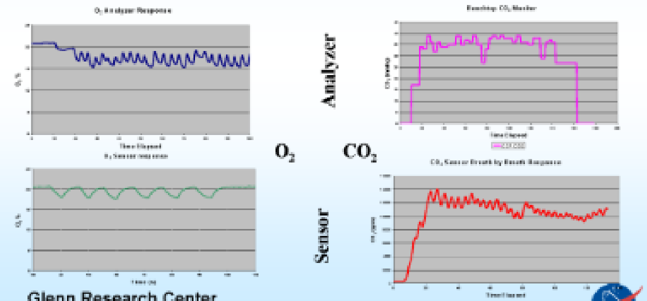
Disease	Compound as a disease marker	Analysis Instrument
Acute cardiac allograft rejection	Pentane	GC/FID
Myocardial infarction (MI)	Hydrocarbons	GC/FID
Asthma	Nitric Oxide	CL analyzer
COPD / ARDS	NO, CO	CL analyzer
Breast Cancer	Pentane	GC/FID
Diabetes	Acetone	GC/FID
Hemolysis	Carbon monoxide	EC CO analyzer GC/TCD
H. pylori infection	$^{13}CO_2$ or $^{14}CO_2$	Isotope Ratio MS Isotope Ratio IR
Alcoholic liver disease	Pentane	GC/FID
Liver cirrhosis	Dimethyl sulfide Volatile fatty acid	GC/FPD GC/FID
Weight Reduction	Acetone	GC/FID

Cleveland Clinic

Breath Sensor Response Data

Breath Sensor System including mouthpiece, sensor manifold, PDA interface, and mini sampling pump

- PROTOTYPE UNITS PRODUCED AND TESTED
- HIGHER TEMPERATURE CO2 AND O2 SENSORS PROVIDED RESULTS COMPARABLE TO THAT OF LAB BENCH INSTRUMENTATION
- BREATH TO BREATH RESOLUTION
- NEED TO TRANSITION TO LOWER TEMPERATURE SENSORS



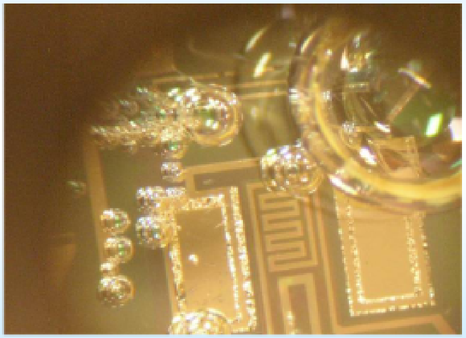
OBJECTIVES OF STATE OF OHIO THIRD FRONTIER PROGRAM

- **This project will establish a pipeline for technology development and product commercialization.**
- **Three basic product types are being developed**
  - **NO based breath Analysis;**
  - **NO/CO Based Breath Analysis;**
  - **Multispecies Based Breath Analysis**
- **The overall approach is to:**
  - **Develop a operational prototype**
  - **Test in Clinical and then Home settings**
  - **Define a manufacturing process**
  - **Introduced to market**
- **Activities in this project will mature into various systems as follows:**
  - **NO based system will be introduced to market, while the**
  - **NO/CO based system will have a defined manufacturing process for market introduction, and**
  - **Multispecies Based Breath Analysis system will be ready for Home studies**

SENSORS HAVE WIDE VARIETY OF APPLICATIONS BUT CANNOT WORK IN EVERY ENVIRONMENT

RIGHT SENSOR FOR RIGHT APPLICATION

H2 SENSOR OPERATION UNDER WATER



SUMMARY

- AEROSPACE APPLICATIONS REQUIRE A RANGE OF CHEMICAL SENSING TECHNOLOGIES
- NEW FAMILY OF GAS SENSOR TECHNOLOGY BEING DEVELOPED TO MEET THESE NEEDS USING:
  - ➢ MICROFABRICATION AND MICROMACHINING TECHNOLOGY, NANOMATERIALS, SiC-BASED SEMICONDUCTOR TECHNOLOGY
- TECHNOLOGY BEST APPLIED WITH STRONG INTERACTION WITH USER/TAILOR SENSOR FOR NEEDS OF APPLICATION/SUPPORTING TECHNOLOGIES MANDATORY
- DRIVE SYSTEM INTELLIGENCE TO THE SENSOR LEVEL
- SENSORS AND SENSOR ARRAYS BEING DEVELOPED
- A RANGE OF LAUNCH, IN-SPACE, AND LUNAR APPLICATIONS
- LONG-TERM: INTELLIGENT SYSTEMS
  - ➢ RELIABILITY
  - ➢ REDUNDANCY
  - ➢ ORTHOGONALITY
  - ➢ CROSS-CORRELATION
- NANOTECHNOLOGY
  - SIGNIFICANT PROMISE BUT TECHNOLOGY BARRIERS EXIST
  - LONG-TERM FULLY ENABLE "LICK AND STICK"

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NANOTECHNOLOGY DEVELOPMENT

NANO DIMENSIONAL CONTROL PREVALENT IN CHEM/BIO SENSORS

- NANO CONTROL OF CHEMICAL SENSOR STRUCTURES STRONGLY PREFERRED EVEN IF SENSOR ISN'T LABELED A "NANO SENSOR"
  - ➢ WE ARE MEASURING VARYING NUMBERS OF MOLECULES
- IF NANOTECHNOLOGY ALREADY PRESENT IN CHEM/BIO SENSOR DEVELOPMENT, THEN:
  - ➢ WHAT STAYS THE SAME AND WHAT'S NEW?
  - ➢ WHAT ARE THE CHALLENGES IN NANOTECHNOLOGY DEVELOPMENT?
  - ➢ WHAT IS THE ROLE/ADVANTAGE OF NANO TECHNOLOGY

SAME

- APPLICATIONS DON'T CARE THAT IT IS NANO, NEED IMPROVED CAPABILITIES
- STANDARD SENSOR TECHNOLOGY REQUIREMENTS, POTENTIAL, AND DIRECTIONS SET BY THE ADVENT OF MICROTECHNOLOGY REMAIN CONSTANT
- SENSITIVITY, SELECTIVITY, STABILITY, RESPONSE TIME, TAILOR FOR THE APPLICATION, "LICK AND STICK", ETC.
- PACKAGING STILL SIGNIFICANT COMPONENT OF SYSTEM
- AS WITH MICRO, CAN ONLY GO AS FAR AS THE SUPPORTING TECHNOLOGIES
- MULTIPLE SENSOR PLATFORMS MAY STILL BE NECESSARY DEPENDING ON THE APPLICATION/ENVIRONMENT

TARGETED TECHNOLOGY DEVELOPMENT

- MICRO-NANO CONTACT FORMATION
- NANOMATERIAL STRUCTURE CONTROL
- OTHER NANO OXIDE MATERIALS

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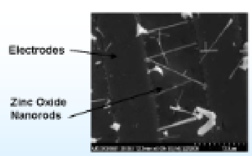
EXAMPLE NANOTECHNOLOGY CHALLENGE: MICRO-NANO CONTACT FORMATION

- NO MATTER HOW GOOD THE SENSOR, IF YOU CANNOT MAKE CONTACT WITH IT, THEN IT WILL NOT BE INEFFECTIVE
- MICRO-NANO INTEGRATION/CONTACTS
  - ➢ MAJOR QUESTION FOR NANOSTRUCTURED BASED SENSORS: HOW ARE THE NANOSTRUCTURED MATERIALS INTEGRATED INTO A MICROSTRUCTURES
- MANUAL METHODS GENERALLY INVOLVE REPEATABILITY ISSUES E.G.
- BASIC WORK ON-GOING TO IMPROVE MICRO-NANO CONTACTS E.G. USE OF DIELECTROPHORESIS TO ALIGN NANOSTRUCTURES
- BRING THE LEVEL OF PROCESS CONTROL PRESENT IN MICROSYSTEMS TO NANOTECHNOLOGY

NANOSTRUCTURE FABRICATED BY THERMAL EVAPORATION-CONDENSATION PROCESS.

NANORODS CONTACTED WITH THE SUBSTRATE VIA A SILVER EPOXY



ZINC OXIDE NANORODS AFTER DIELECTROPHORESIS ACROSS INTERDIGITATED FINGERS

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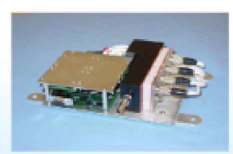
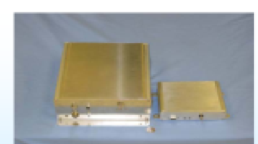
CREW EXPLORATION VEHICLE FIRE DETECTION

- Development of Miniaturized MultiParameter Smart Space Fire Detection System based on:
  - ➢ MMFDS sensors and approach
  - ➢ "Lick and Stick" sensor platform being qualified for CLV applications
- System features include
  - ➢ 4 Chemical sensors for fire detection, 2 CO, H2/HxCy, CO2 sensor
  - ➢ 2 sensors to measure the environment humidity and pressure
  - ➢ Small pump for air flow
  - ➢ Basic core hardware of the "Lick and Stick" platform, e.g., the similar electronics.



Miniaturized MultiParameter Smart Space Fire Detection System: 4 Chemical Sensors, physical sensors, and circulation pump



Comparison of MMFDS (10" x 10" x 4.50") to Miniaturized MultiParameter Smart Space Fire Detection System (7.00" x 5.85" x 2.12")

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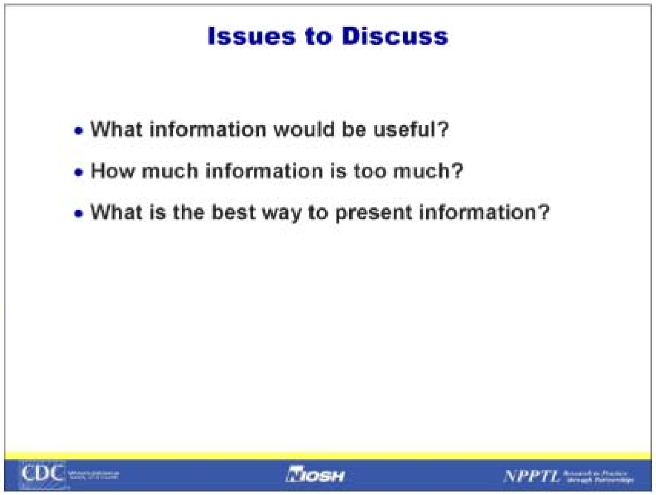
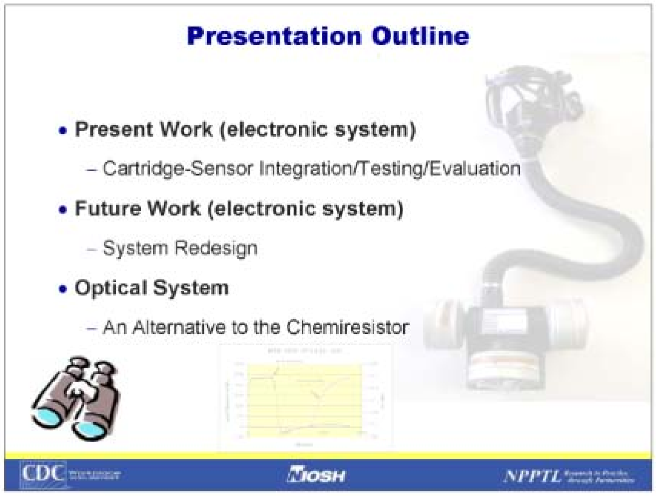
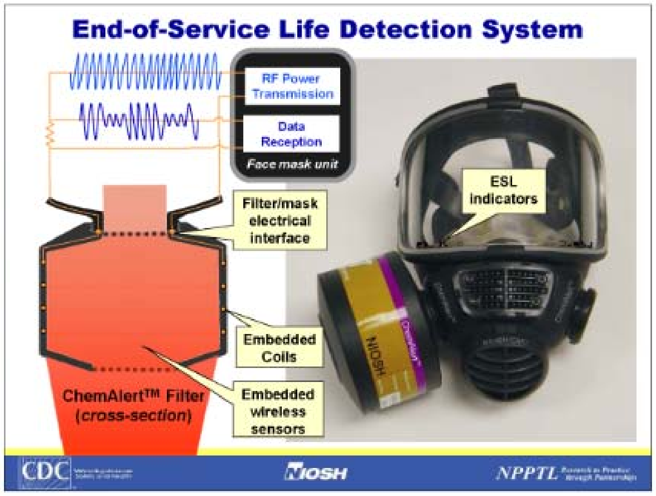
Appendix J Sensor Development for ESLI & Its Application to Chemical Detection – Jay Snyder (NIOSH/NPPTL)







Collaboration with Respirator Manufacturers

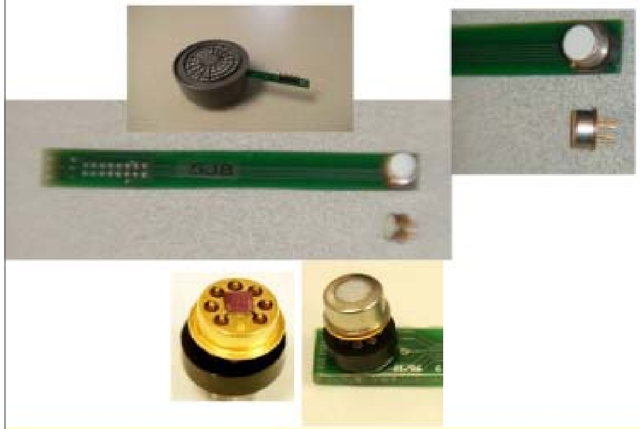
- Dräger
- MSA
- North Safety Products
- Scott Health & Safety
- Sundström Safety AB
- Survivair

CDC NIOSH NPPTL

Sensor Integrated Cartridge

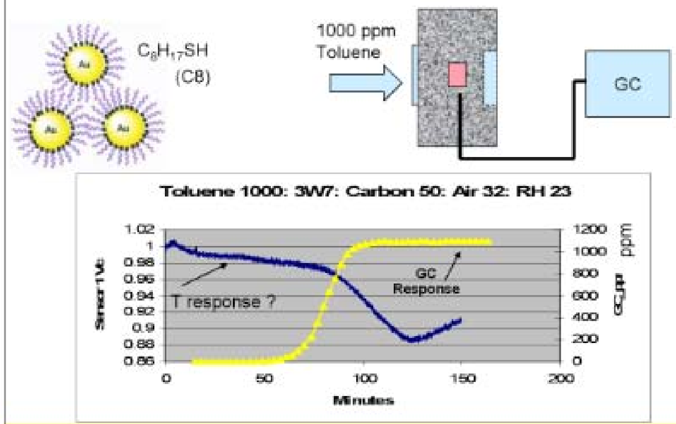
CDC NIOSH NPPTL

Sensor Options for Integration



CDC NIOSH NPPTL

Performance of a CGNP



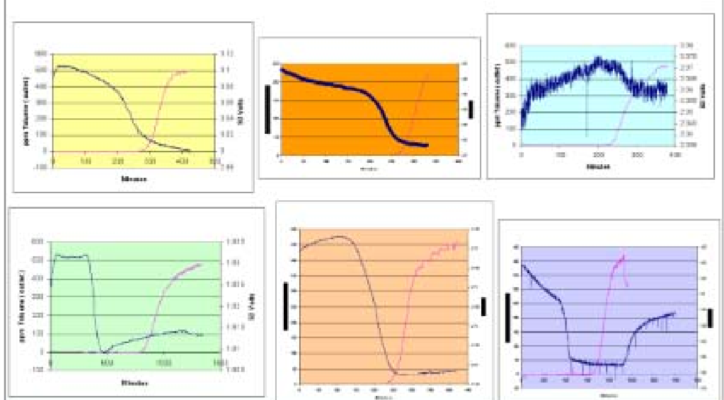
CDC NIOSH NPPTL

Examples of Sensor Integrated Cartridges

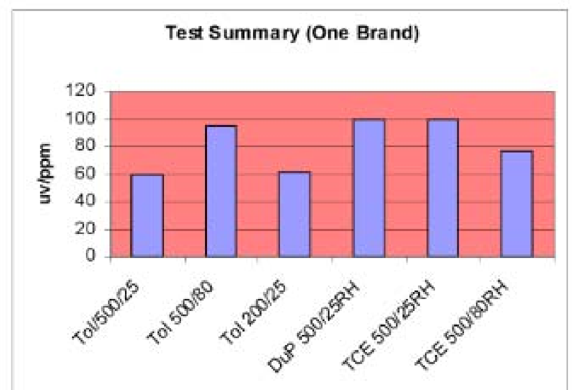
Solvents and Test Setup

- Toluene (500 & 200 ppm)
- DuPont Enamel Reducer (500 ppm)
  - 19+ groups of compounds
- Trichloroethylene (500 ppm)
- 25 & 80 % RH
  - Custom chamber
  - 32 l/min flow
  - Controlled analyte and humidity

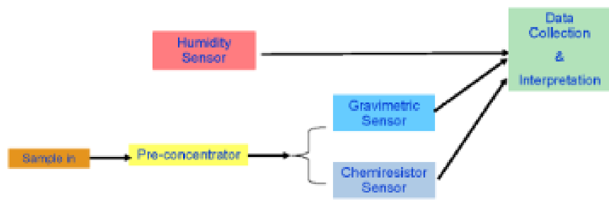
Toluene-500ppm-25%RH



Test Results



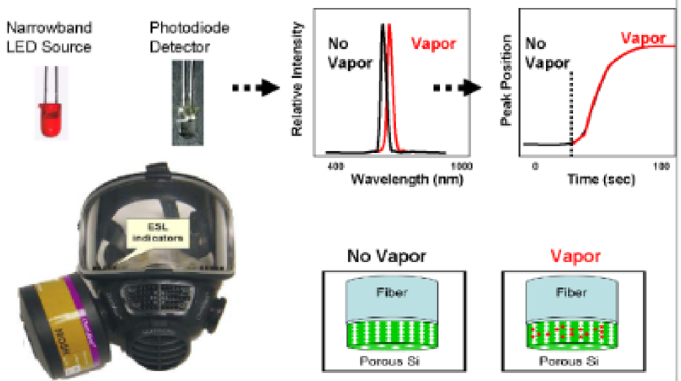
Future Generation MEMS Device



Continuing Work

- Powered Air Purifying Respirator (PAPR) Study
- Support for the PAPR Draft Concept
- Wireless Feasibility Investigation

Optical Fiber Sensing Scheme



Summary

- Cartridge/Sensor integration has been successfully completed.
- PAPR module support.
- Continued development and refinement of the MEMS and optical detection systems.

Quality Partnerships Enhance Worker Safety & Health

Visit Us at: http://www.cdc.gov/niosh/npptl/default.html

Disclaimer:

The findings and conclusions in this presentation have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy.

Thank you

CDC NIOSH NPPTL

Appendix K Engineering Considerations – Paul Greenberg (NASA)

Engineering Considerations

Real-Time Monitoring of Total Inward Leakage of Respiratory Equipment Used by Emergency Responders

(RTMTILREUFR)

National Institute of Standards and Technology
May 1st, 2009

NIST: Real-Time Monitoring of Respiratory Threats May 1st, 2009

What do we mean by Engineering "Considerations"…?

I. Environmental Considerations (Implicit in Field applications)

- Temperature
- Humidity
- Shock
- Vibration
- Physical orientation
- Corrosive, reactive, or flammable surroundings

NIST: Real-Time Monitoring of Respiratory Threats May 1st, 2009

Engineering "Considerations" (cont'd.):

II. Packaging Considerations/Physical Attributes

- Size/volume
- Mass
- Power Consumption
- Durability

III. Application-Specific Considerations

- Physical sampling (ambient pressure or flow); avoiding potential biases
- Conditional sampling (data rate reqt's., correlated vs. random sampling)
- Form, fit and function: user compatibility for specific field situation

NIST: Real-Time Monitoring of Respiratory Threats May 1st, 2009

Quotes worth noting…

"A Firefighter is not a Christmas tree. You cannot simply hang ornaments on them as you please."

"If you give a Firefighter three stainless steel balls, within twenty minutes, he will have lost one and broken the other. He will have given the third to someone in EMS, who will have lost or broken it as well."

R. Stephen, Montgomery County Maryland HazMat

NIST: Real-Time Monitoring of Respiratory Threats May 1st, 2009

Engineering "Considerations" (cont'd.):

IV. Operational Considerations

- Data logging and/or wireless transmission; data transfer
- Internal processing: providing the answer vs. providing raw data
- Duration of event(s) of interest
- Overall anticipated service life
- Reliability
- Visibility and operability (i.e. user interface)
- Cost and number of units required
- Calibration and calibration interval
- Requirement for internal health-status monitoring: "Is my sensor working?"

NIST: Real-Time Monitoring of Respiratory Threats May 1st, 2009

Engineering "Considerations" (cont'd.):

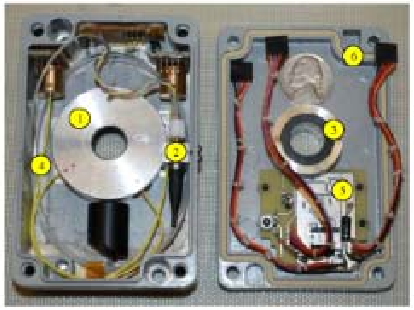
V. Scaling and Fabrication Considerations

- Physics of scaling: simply making an existing sensor smaller generally doesn't work.
- An alternative or completely new measurement approach may be required.
- This may introduce issues such as materials compatibility issues, or sub-element inter-operability considerations.
- Different or possibly novel methods of fabrication may be required.

Summary: *Effective solutions often require creative ways of thinking*

NIST: Real-Time Monitoring of Respiratory Threats May 1st, 2009

A few examples in practice ...



Multi-moment particulate sensor

1. Shock and vibration resistant mono-block optics assembly.

   Inherent optical design immune to thermal and mechanical drift.
2. Fiber-coupled laser source: low power consumption; provides diffraction-limited beam quality required by virtue of close source-detector proximity.
3. Flow-through design accommodates both passive and active sampling.
4. Fiber-couple receivers provide matched confocal apertures to reject stray light and background.
5. Embedded processor: i) internal calibration constants, ii) algebraic operations to calculate moments, iii) data formatting, iv) health status monitoring, v) field-programmable acquisition interval.
6. Hermetically sealed case.

   [Wireless data transmission not shown]

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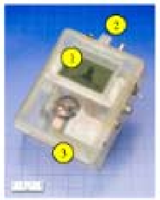

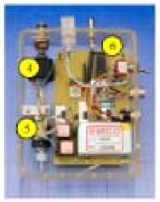

Miniature Differential Mobility Analyzer (DMA)

1. Backlit display for dim viewing conditions.
2. Bi-directional communication port.
3. "Hand-held friendly" enclosure.
4. "Clean slate" design results in classifier module of significantly reduced size.
5. "Clean slate" slate design provides unipolar field charger with improved efficiency and lower voltage operation.
6. Embedded processor: i) system control, ii) internal calibration tables, iii) best-fit data regression, iv) display driver, v) data formatting and output handshaking.

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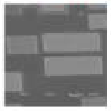
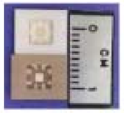
- Novel sensor materials for improved sensitivity, high temperature compatibility, and access to multiple species of interest.
- Flexible platform readily adaptable to a variety of sensor inputs.
- Embedded processor for system control, internal calibration, and data formatting.
- Wireless transmission capability.

"Lick and Stick" Multi-species Leak Detector

Supporting tech development:

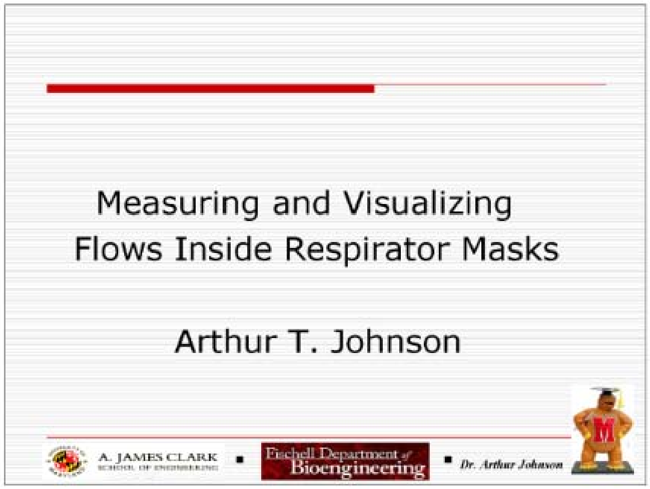


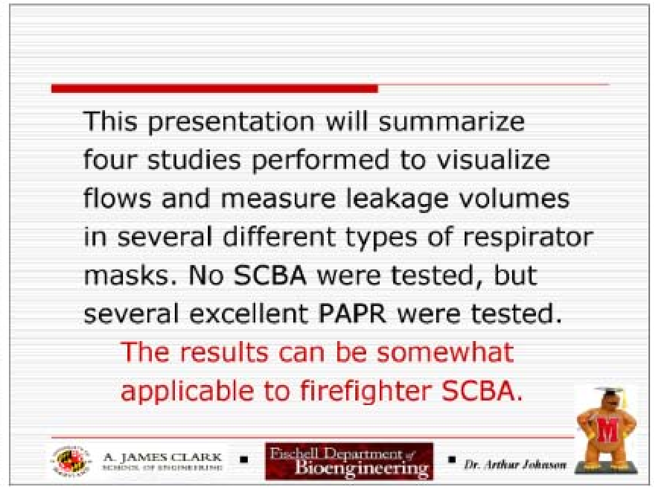


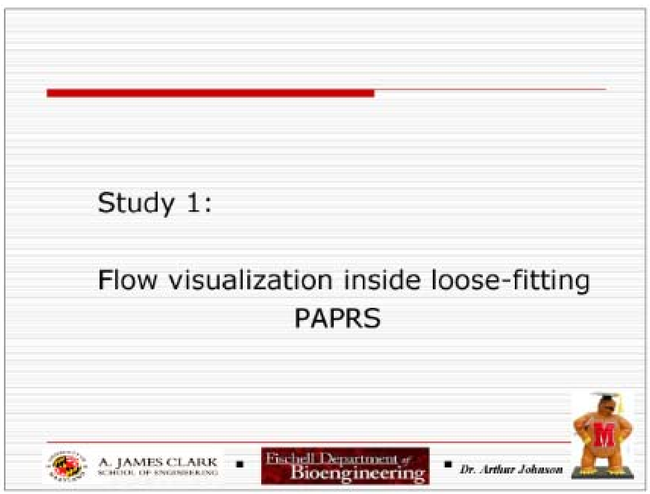
NIST: Real-Time Monitoring of Respiratory Threats

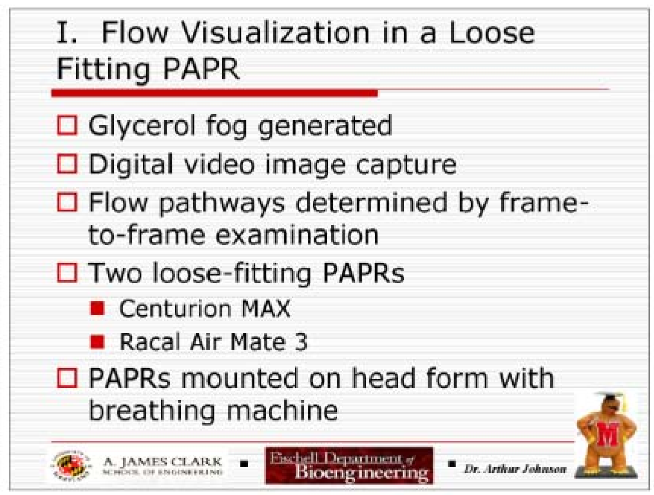
May 1st, 2009

Appendix L Measuring and Visualizing flows Inside Respirator Masks – Arthur Johnson (University of Maryland at College Park









I. Flow Visualization in a Loose Fitting PAPR

- Portable breathing chamber used to contain fog
- Headform covered with black electrical tape to enhance fog visibility.
- Thread fixed at mouth to identify inhalation/exhalation phase
- Light emitting diode added to aid digital frame timing.

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I. Flow Visualization in a Loose Fitting PAPR

Centurion Max with scarf

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I. Flow Visualization in a loose fitting PAPR

Portable Breathing Chamber (PBC)

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I. Flow Visualization in a Loose Fitting PAPR

Centurion Max with scarf movie

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I. Flow Visualization in a Loose-Fitting PAPR

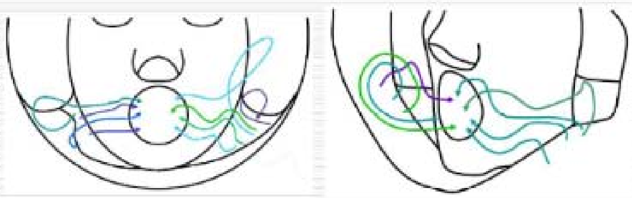

Diagram of flow pathways

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I. Flow Visualization in a Loose-Fitting PAPR

- Flow pathways contorted, twisted, and multilayered

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I. Flow Visualization in a Loose-Fitting PAPR

Racal with fog and no scarf

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I. Flow Visualization in a Loose-Fitting PAPR

- Fog is drawn in behind Racal Air Mate 3 face shield by blower turbulence.
- Almost entire face area filled with fog during all breathing phases.

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Study 2:

Flow leakage in tight-fitting PAPRs.
(Most of these have opaque facepieces, making flow visualization very difficult)

II. Inward Leakage in Tight-Fitting PAPRs

- Digital video image captured
- PAPRs mounted on head form with breathing machine
- Bronchoscope located at the mouth of the headform to detect inhaled fog
- Flow rates measured at blower and breathing machine

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II. Inward Leakage in Tight-Fitting PAPRs

- Two light emitting diodes to detect inhalation and determine timing
- Flow rate difference = leakage flow
- 3M Breathe Easy PAPR
- SE 400 Breath-responsive PAPR

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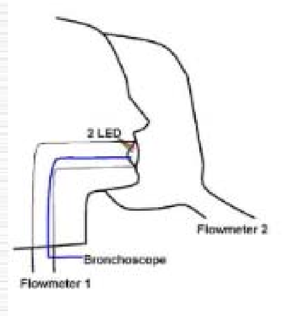
II. Inward Leakage in Tight-Fitting PAPRs



- **Schematic diagram of the experimental arrangement with flow meters, light-emitting diodes, PAPR, head form, and bronchoscope.**

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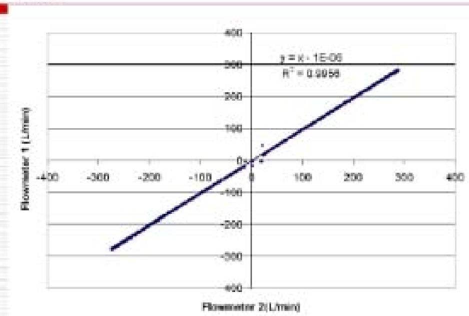
II. Inward Leakage in Tight-Fitting PAPRs



Comparison of two flowmeter calibrations

II. Inward Leakage in Tight-Fitting PAPRs

- Because the two flowmeters are identical, flow rate differences can be measured accurately.
- The results allow determination of leakage flow rates and volumes (integrated flows).

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II. Inward Leakage in Tight-Fitting PAPRs

- Blower flow rates during inhalation are not constant
- Breathing machine flow rates during inhalation exceed blower flow rates
- Negative blower flows mean backward flow during exhalation
- Leakage volumes approximately 0.21L

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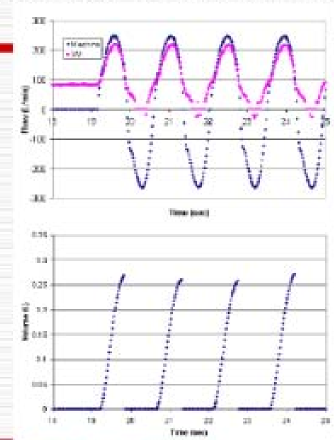
II. Inward Leakage in Tight-Fitting PAPRs

3M Breathe Easy Flowrates (top) and leakage volumes (bottom)



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II. Inward Leakage in Tight-Fitting PAPRs

- **Results**
  - No fog detected at mouth with either PAPR
  - Exhalation valve flutter observed for both PAPRs

Study 3:

Flow visualization inside loose-fitting PAPRS while they are worn by humans, not breathing machine head forms.

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III. Human Subject Testing of Leakage in a Loose-Fitting PAPR

- Glycerol fog generated
- Ten human volunteers
- Centurion MAX PAPR
- Subjects sitting in chamber leaning into transparent film
- Deep inspiration

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III. Human Subject Testing of Leakage in a Loose-Fitting PAPR

- Blower flow measured
- Mouth flow measured with pneumotach in mouth
- Digital video images captured
- Face blackened to improve contrast with fog
- Deep inspirations

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III. Human Subject Testing of Leakage in a Loose-Fitting PAPR

- **Picture of subject in chamber, wearing Centurion MAX**

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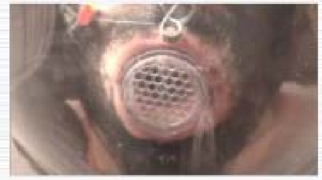
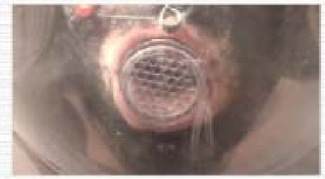
III. Human Subject Testing of Leakage in a Loose-Fitting PAPR





- **close-up of subject with pneumotach**
  with no fog **with fog**

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III. Human Subject Testing of Leakage in a Loose-Fitting PAPR

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III. Human Subject Testing of Leakage in a Loose-Fitting PAPR

- **Results**
  - Flow pathway inside facepiece is twisted and curled

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III. Human Subject Testing of Leakage in a Loose-Fitting PAPR

- **Conclusions**
  1. Dead volume can be protective
  2. Twisted flow pattern increases leakage pathway to the mouth
  3. Protective dead volume was measured at 1.1L
  4. Regions of high & low contaminant concentrations inside face piece can make representative concentrations a challenge

Study 4:

Measurement of actual protection factors for human wearers, not respirators, and blower effectiveness in PAPRs. (It is the contamination that reaches the mouth that is important, not contaminants inside the face piece.)

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IV. Protection Factors and Net Contaminant Volumes Inhaled While Wearing Respirators

- CO_2 used as tracer gas in surrounding air
- Breathing machine used
- Blower inlet, or APR inlet, supplied with standard air
- CO_2 in exhaled breath collected and measured
- Respirator supply flow measured
- Breathing machine flow measured

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IV. Protection Factors and Net Contaminant Volumes Inhaled While Wearing Respirators

- Wearer protection factor is based upon CO_2 inhaled.
- CO_2 can only enter through leaks. Thus, volume of CO_2 collected directly indicates leakage volume.

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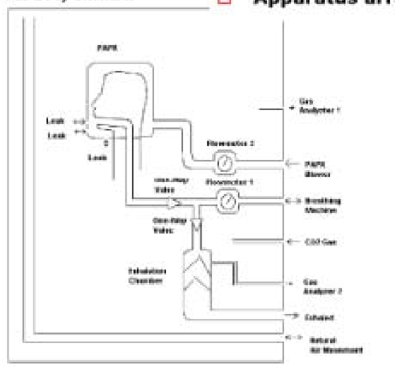
IV. Protection Factors and Net Contaminant Volumes Inhaled While Wearing Respirators

- Apparatus arrangement



IV. Protection Factors and Net Contaminant Volumes Inhaled While Wearing Respirators

- CO_2 is inhaled by the breathing machine from the inside of the respirator and exhaled to the collection chamber.
- CO_2 concentration in the exhalation chamber is measured.

IV. Protection Factors and Net Contaminant Volumes Inhaled While Wearing Respirators

- Wearer (not RPD) protection factor = [CO_2 conc. (exh.)] / [CO_2 conc. (amb.)]

IV. Protection Factors and Net Contaminant Volumes Inhaled While Wearing Respirators

Respirator	Blower flow rate (L/min)	Exhalation Volume (L)	CO_2 Ratio	Protection Factor	Leakage Volume (L)
Racal PAPR	191-200	2.41	.84	1.1	2.02
Centurion PAPR	88-101	2.37	.25	4	0.60
3M Hood PAPR	157-161	2.39	0	∞	0
3M PAPR	121-278	2.42	0	∞	0
SE400 PAPR	64-322	2.32	0	∞	0
SE400 APR (blower off)	0-284	2.37	0.048	20	0.11
FRM 40 APR	0-289	2.37	0.057	17	0.14

IV. Protection Factors and Net Contaminant Volumes Inhaled While Wearing Respirators

- **Questions:**
  - Does all inspired air come from blower?
    - Leakage
  - Is all blower air inspired?
    - Blower effectiveness

IV. Protection Factors and Net Contaminant Volumes Inhaled While Wearing Respirators

- Blower effectiveness: some blower flow can escape to the outside without supplying inhaled air.

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IV. Protection Factors and Net Contaminant Volumes Inhaled While Wearing Respirators

- $V_{bl,inh} = V_{inh}$ [1 – CO_2 ratio]
- $V_{bl,tot}$ = integrated blower flow rate
- Blower effectiveness = $V_{bl,inh} / V_{bl,\ tot}$

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IV. Protection Factors and Net Contaminant Volumes Inhaled While Wearing Respirators

- A blower effectiveness of 1.0 indicates all blower air contributes to the volume of air inhaled.
- A blower effectiveness less than 1.0 indicates that some of the blower air is lost to the outside, and is not inhaled.
- A blower effectiveness greater than 1.0 indicates that blower air delivered during the exhalation phase accumulates inside the respirator and is breathed in during the next inhalation phase.

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IV. Protection Factors and Net Contaminant Volumes Inhaled While Wearing Respirators

Respirator	Blower flow rate (L/min)	CO_2 ratio	Inhaled volume (L)	Blower Contribution (L)	Integrated Blower Flow (L)	Blower Effectiveness
Racal PAPR	191-200	0.84	2.66	0.43	2.42	0.18
Centurion PAPR	88-101	0.25	2.66	1.99	1.17	1.70
3M Hood PAPR	157-161	0	2.63	2.63	1.87	1.41
3M PAPR	121-278	0	2.62	2.62	2.51	1.04
SE 400 PAPR	64-322	0	2.58	2.58	2.90	0.89
SE 400 APR (blower off)	0-284	0.048	2.58	2.46	2.50	0.98
FRM 40 APR	0-289	0.057	2.62	2.47	2.51	0.99

IV. Protection Factors and Net Contaminant Volumes Inhaled While Wearing Respirators

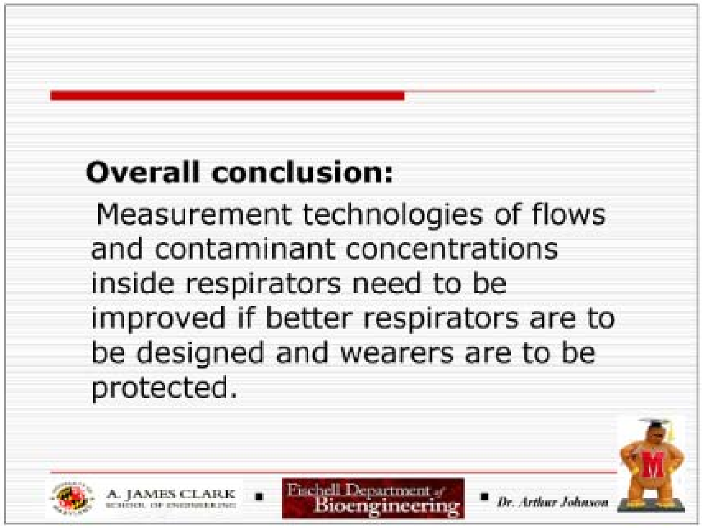
- **Representative Results**
  - 3M Breathe Easy PAPR
    - Low leakage volume (0 L)
    - High protection factor (∞)
    - Medium blower effectiveness (1.0)
- **Conclusion**
  - Blower supplies inhaled air

Conclusions from all four studies

1. There can be significant leakage in a loose fitting PAPR
2. Protective dead volume is important
3. Flow pathway for contamination to mouth can be made long by vortex folding
4. Blowers should function by cleaning dead volume of contamination during exhalation phase

Conclusions from all four studies

5. Blowers do not need to supply peak flow rate
6. Measurements of contaminant concentration inside the face piece can be incorrect, given that there are regions of high and low contaminant concentrations in close proximity.
7. Wearer protection factors do not agree well with expected respirator protection factors.


Overall conclusion:
Measurement technologies of flows and contaminant concentrations inside respirators need to be improved if better respirators are to be designed and wearers are to be protected.
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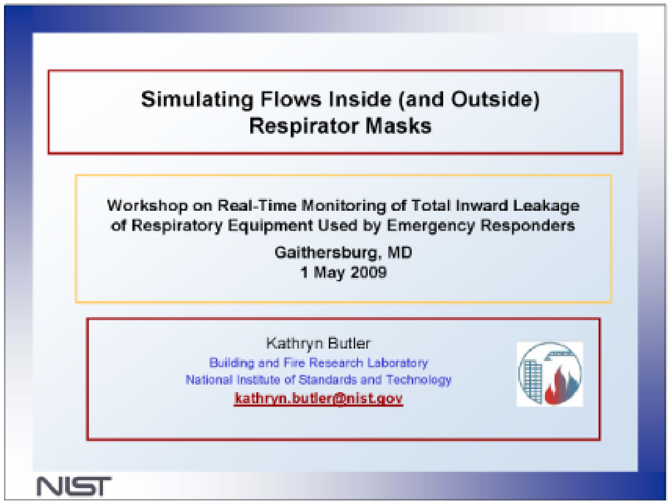
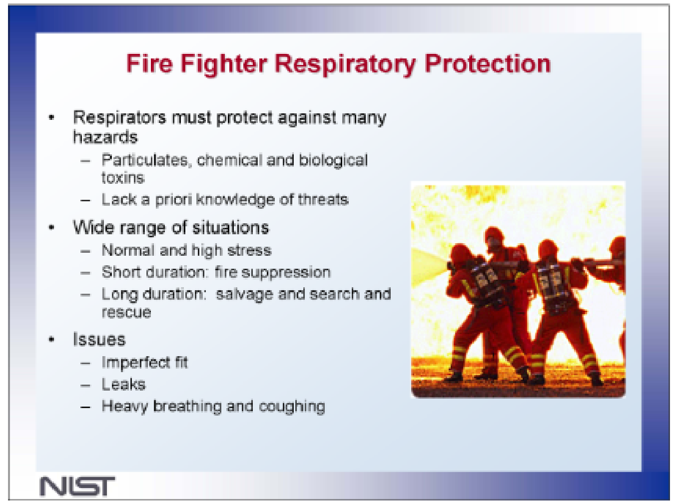
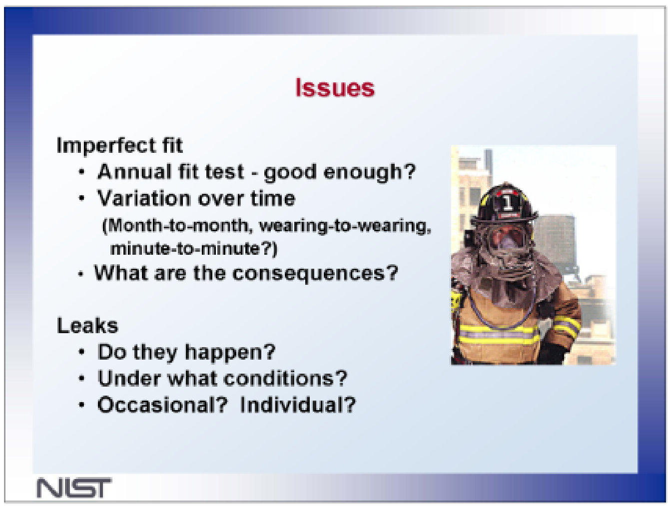
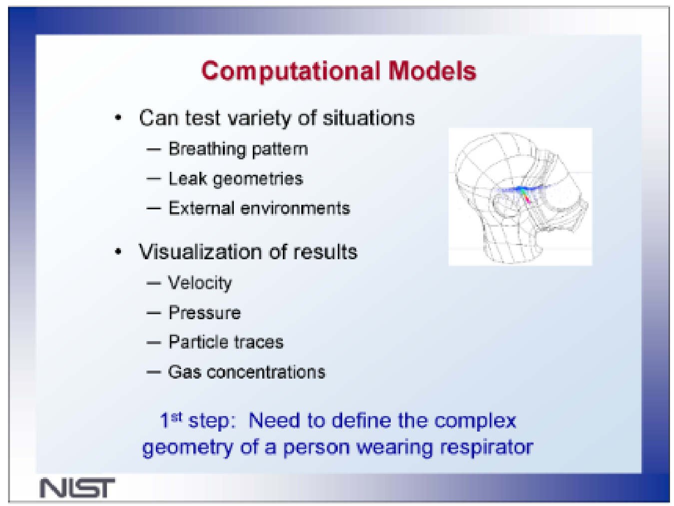
Fischell Department of Bioengineering
Dr. Arthur Johnson

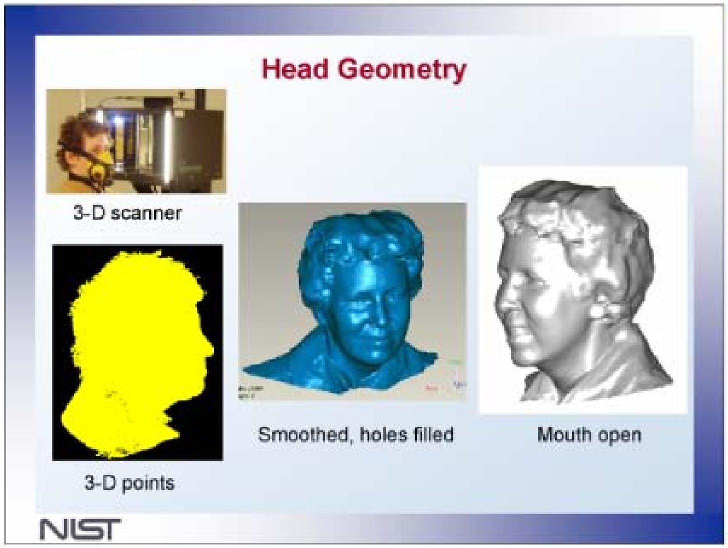
Appendix M Simulating Flows Inside (and Outside) Respirator Masks – Kathryn Butler (NIST)

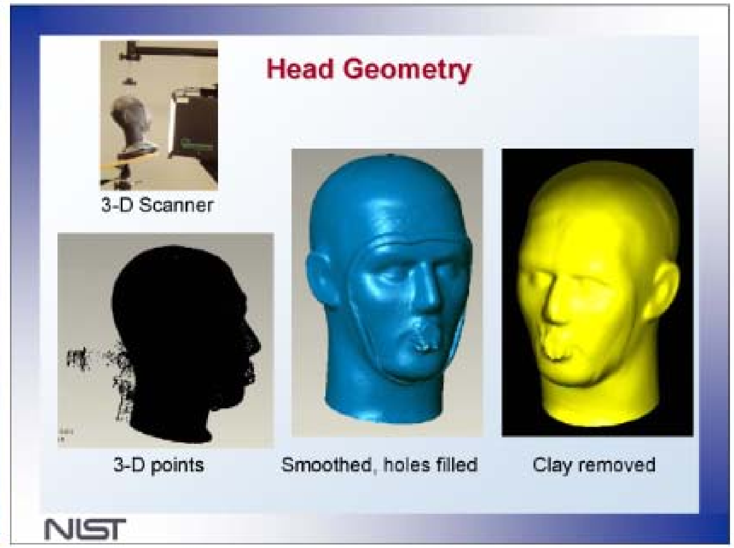


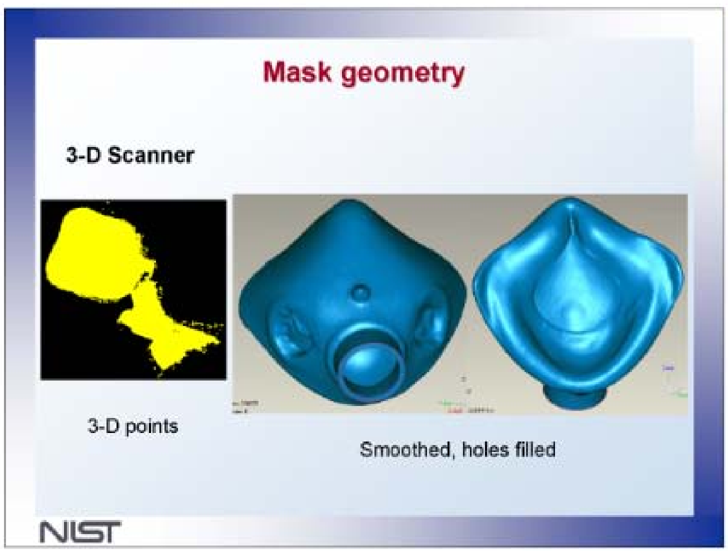


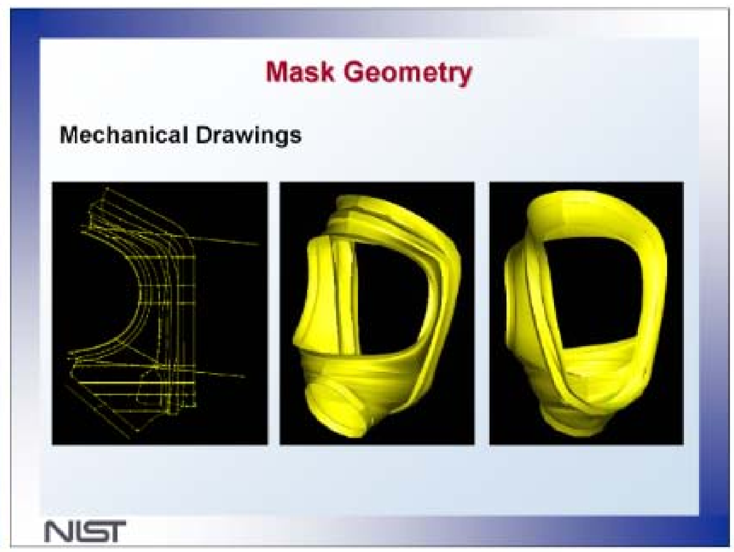





Head Geometry
3-D scanner
3-D points
Smoothed, holes filled
Mouth open
NIST

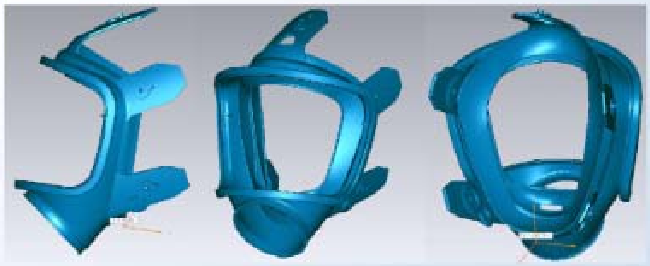

Head Geometry
3-D Scanner
3-D points
Smoothed, holes filled
Clay removed
NIST


Mask geometry
3-D Scanner
3-D points
Smoothed, holes filled
NIST


Mask Geometry
Mechanical Drawings
NIST

Mask Geometry

CAD



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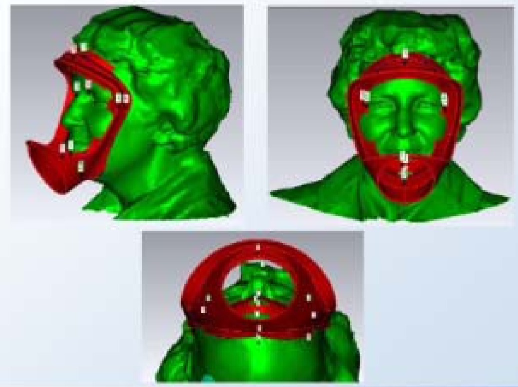
Putting the respirator on the face is not as easy as it seems



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Question: What would be the effect of an external leak from a Closed Circuit SCBA?

- Recirculates exhaled air by absorbing CO_2 and adding fresh oxygen
- Oxygen cylinder replaces compressed air cylinders
- Up to four hours of use
- Oxygen content within respirator may exceed 60 %
- What is the additional hazard in a fire environment?

- project funded by NIOSH/NPPTL

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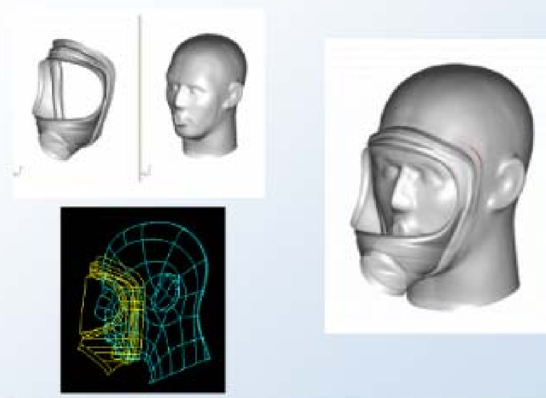
Define external leak



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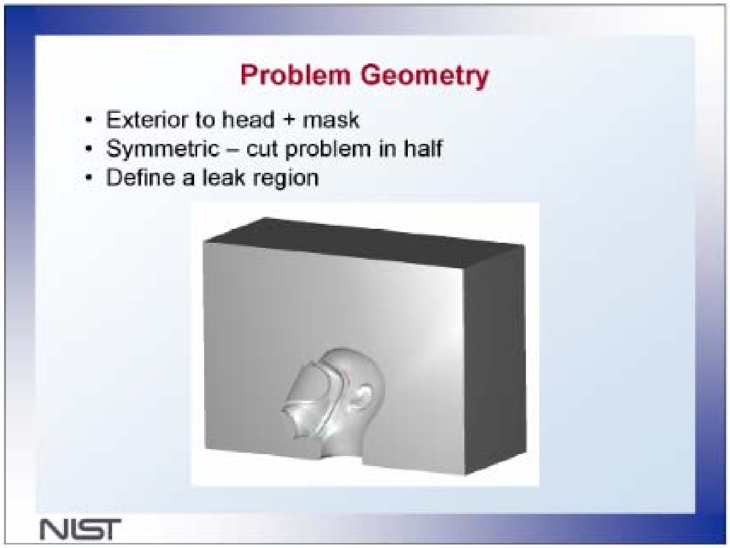
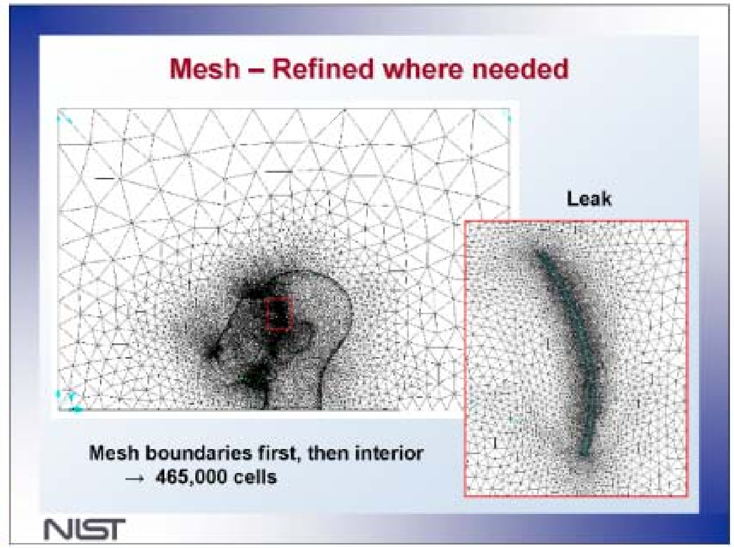
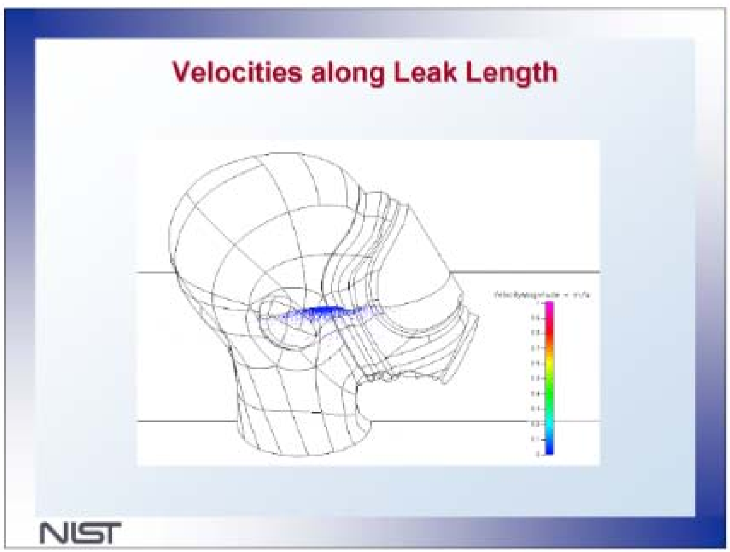
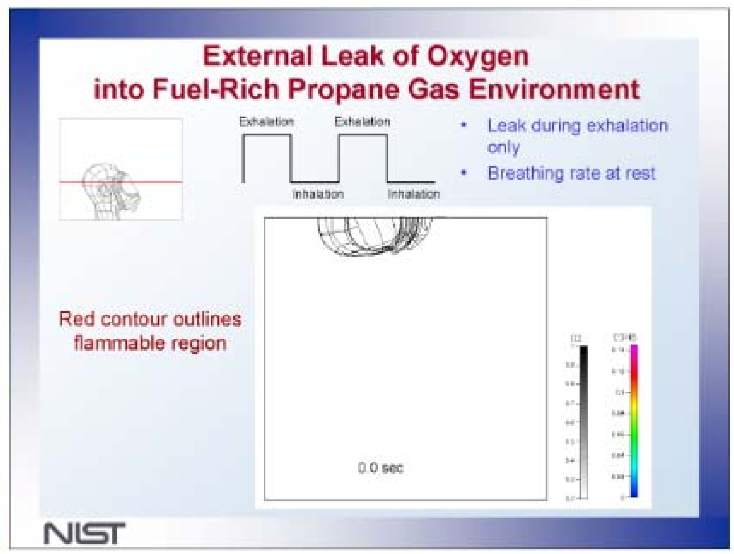
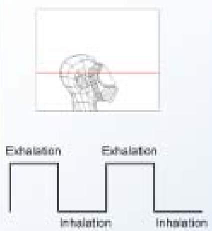

Problem Geometry
• Exterior to head + mask
• Symmetric – cut problem in half
• Define a leak region

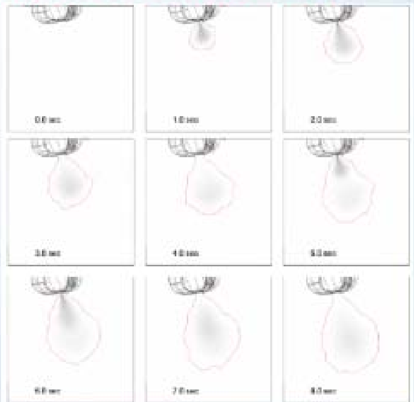

Mesh – Refined where needed
Leak
Mesh boundaries first, then interior
→ 465,000 cells


Velocities along Leak Length


External Leak of Oxygen
into Fuel-Rich Propane Gas Environment
Exhalation
Exhalation
Inhalation
Inhalation
• Leak during exhalation only
• Breathing rate at rest
Red contour outlines flammable region
0.0 sec

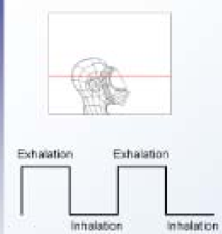
External Leak of Oxygen into 10 % Propane Gas Environment





- Leak during exhalation only
- Breathing rate at rest

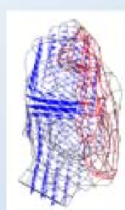
External Leak of Air into 10 % Propane Gas Environment



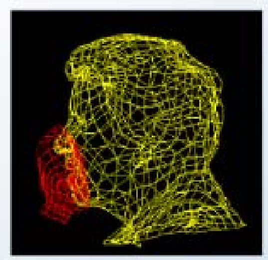
- Leak during exhalation only
- Breathing rate at rest

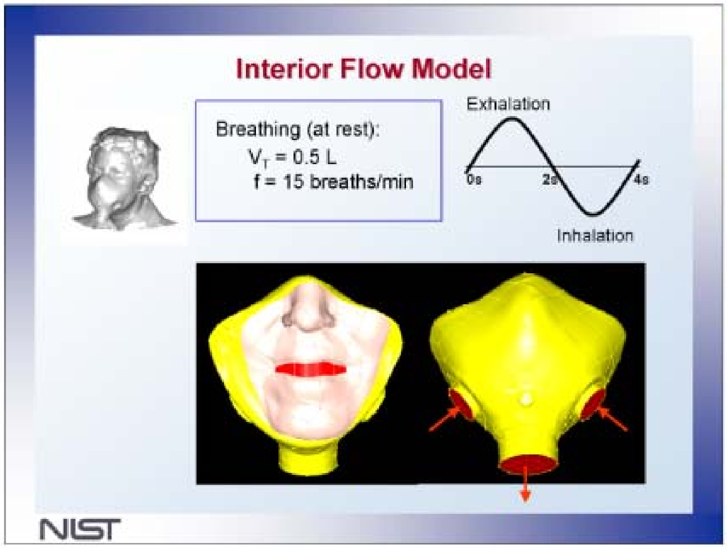
What is the internal flow field for a respirator?

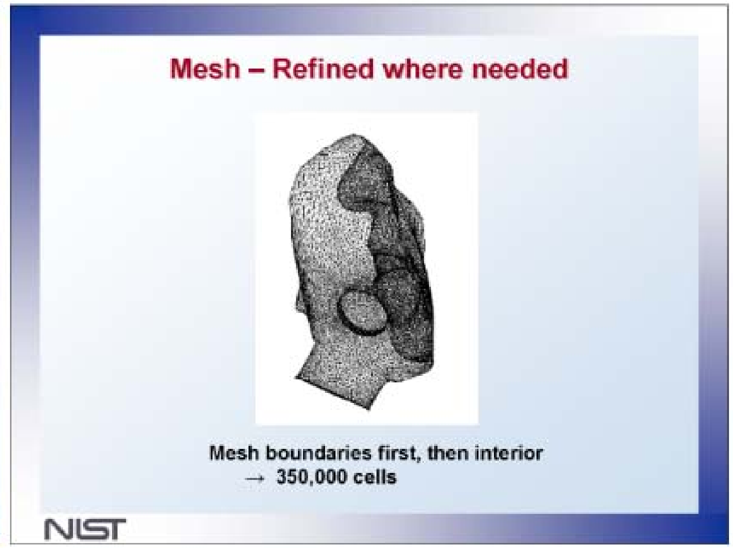
- Where are the best positions for monitoring flow, pressure, gas concentrations?
- How is the flow affected by a leak?
- What breathing resistance does the user experience?

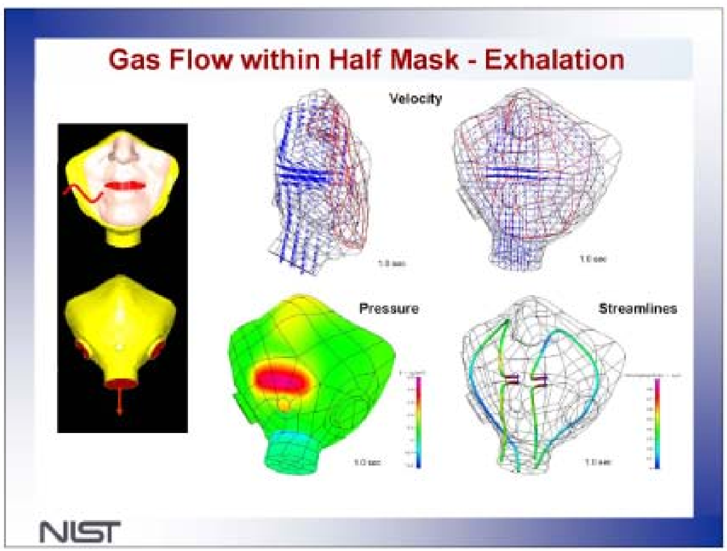


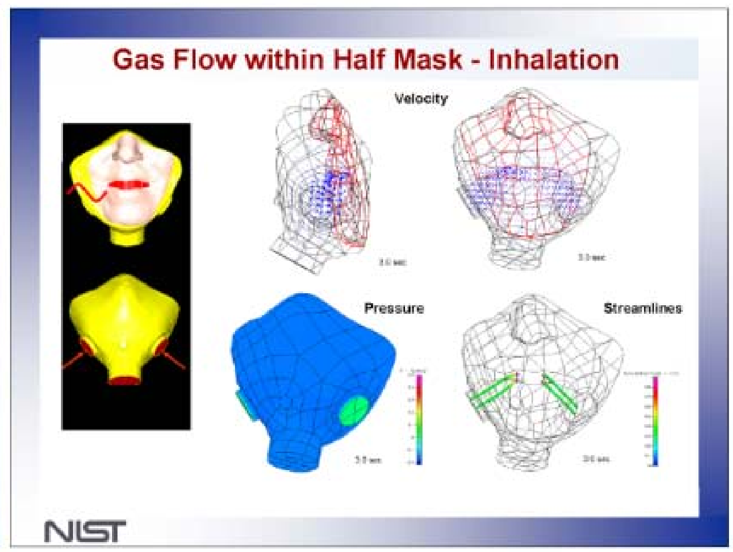
Prepare the Geometry

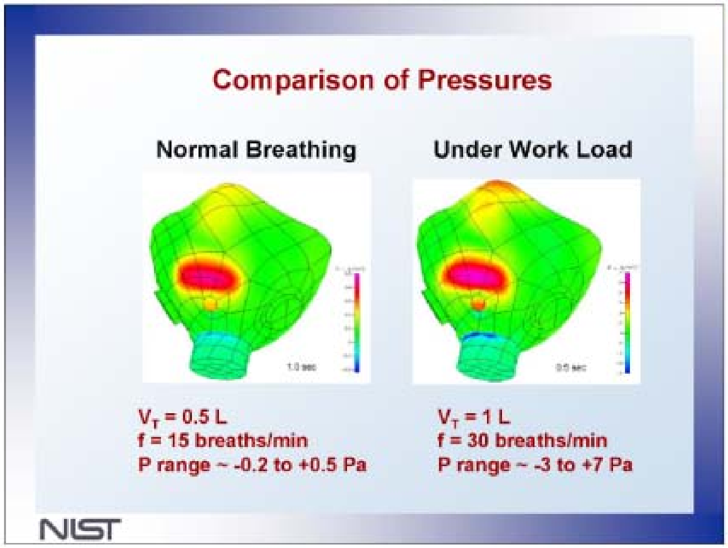


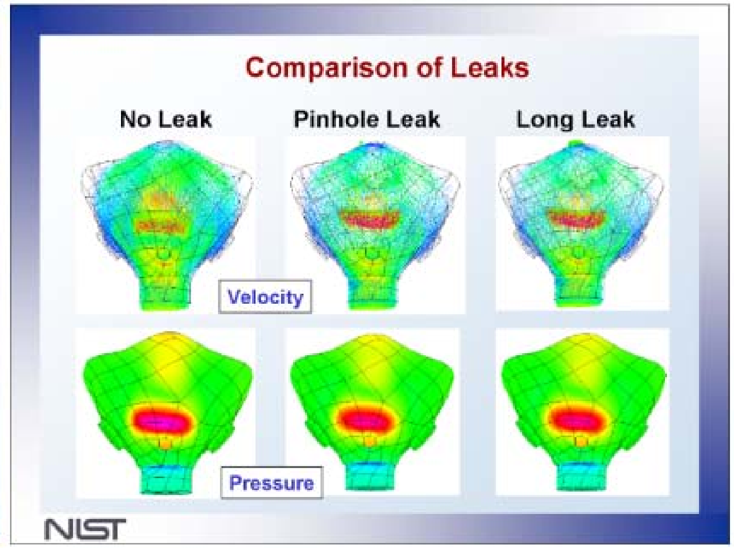

Interior Flow Model
Breathing (at rest):
V_T = 0.5 L
f = 15 breaths/min
Exhalation
0s
2s
4s
Inhalation
NIST

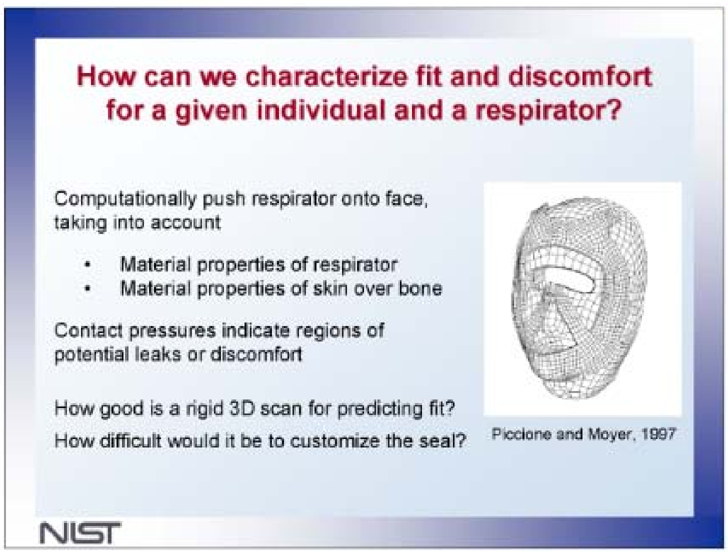

Mesh – Refined where needed
Mesh boundaries first, then interior
→ 350,000 cells
NIST

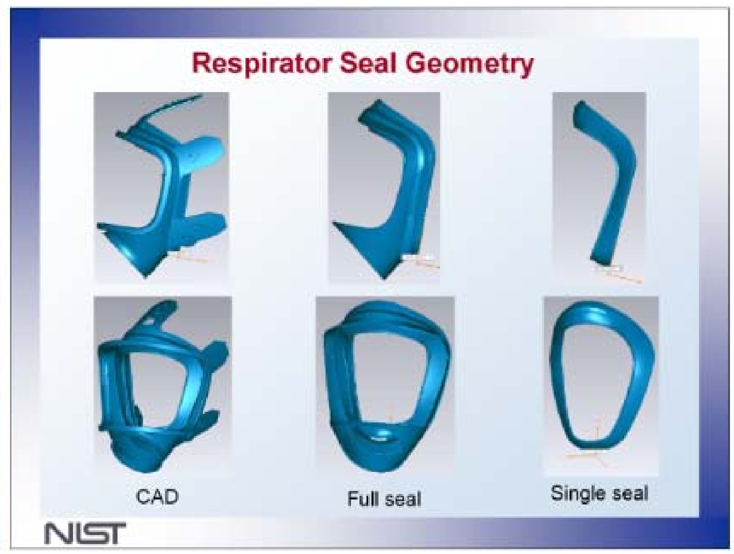

Gas Flow within Half Mask - Exhalation
Velocity
Pressure
Streamlines
NIST


Gas Flow within Half Mask - Inhalation
Velocity
Pressure
Streamlines
NIST

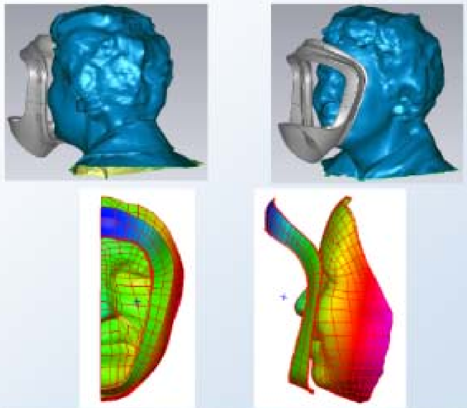

Comparison of Pressures
Normal Breathing
Under Work Load
V_T = 0.5 L
f = 15 breaths/min
P range ~ -0.2 to +0.5 Pa
V_T = 1 L
f = 30 breaths/min
P range ~ -3 to +7 Pa
NIST


Comparison of Leaks
No Leak
Pinhole Leak
Long Leak
Velocity
Pressure
NIST


How can we characterize fit and discomfort for a given individual and a respirator?
Computationally push respirator onto face, taking into account
• Material properties of respirator
• Material properties of skin over bone
Contact pressures indicate regions of potential leaks or discomfort
How good is a rigid 3D scan for predicting fit?
How difficult would it be to customize the seal?
Piccione and Moyer, 1997
NIST


Respirator Seal Geometry
CAD
Full seal
Single seal
NIST

Initial Position of Seal



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