MICROFABRICATED CHEMICAL SENSORS FOR SPACE HEALTH MONITORING APPLICATIONS

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ABSTRACT
The monitoring of chemical species is an important component of an overall health monitoring system for space vehicles. Three areas of interest are fuel leak detection, fire detection, and emission monitoring. This paper reviews the microfabricated chemical sensor technology being developed to address the needs of these very different applications. This development utilizes MicroElectroMechanical Systems (MEMS) based technology, nanomaterials, and high temperature Silicon Carbide semiconductors. Application of these sensors on, for example, the Space Shuttle is discussed.

INTRODUCTION
The monitoring and management of the health of both space vehicles and space operating systems depends on the ability to detect a variety of parameters including chemical gas species. Three applications of particular interest are the monitoring of fuel leaks, fire detection, and the monitoring of emissions from high temperature, harsh environments such as propulsion systems or chemical processing reactors.

In leak monitoring of launch vehicles, detection of low concentrations of hydrogen and other fuels is important to avoid explosive conditions that could harm personnel and damage the vehicle. Dependable vehicle operation also depends on the timely and accurate measurement of these leaks. In 1990, hydrogen leaks on the Space Shuttle while on the launch pad temporarily grounded the fleet until the leak source could be identified. As recently as July 1999, the launch of STS-93 was delayed for two days due to an ambiguous signal using the present leak detection system. Thus, the detection of explosive concentrations of fuel continues to be of interest, not only on the launchpad but wherever the fuel is used.

Further, since an explosive condition depends not only on the amount of fuel present but the oxygen concentration as well, the simultaneous measurement of both fuel and oxygen is an important component of a leak detection system. In future space propulsion systems, the fuel could be hydrogen, as presently used on the Shuttle, or hydrocarbons such as propane, methane, ethanol, and hydrazine. Thus, the development of multiple sensors (a sensor array) to determine the concentration of hydrogen or hydrocarbon fuels as well as oxygen is necessary for space applications.

The detection of fires on-board space and commercial aircraft is extremely important to avoid catastrophic situations and to verify the operational status of the vehicle. The standard method of fire
detection is the use of smoke detectors which are either optically based or depend on the ionization of particles. Although these smoke detection systems are often highly developed and very sensitive, they do have a problematic rate of false alarms with estimated false alarm rates varying from 10:1 to 500:1. The presence of false alarms decreases the confidence in these systems and may potentially cause accidents if personnel react to reported fires that may not exist. These false alarms may be caused by a number of sources including: changes in humidity, condensation on the fire detector surface, and contamination from the contents of the vehicle.

A second, independent method of fire detection to complement the conventional smoke detection techniques, such as the measurement of chemical species indicative of a fire, will help reduce false alarms and improve aircraft safety. Although many chemical species are indicative of a fire, two species of particular interest are carbon monoxide (CO) and carbon dioxide (CO$_2$). Different types of fires produce different chemical signatures; the sensor must be able to detect the presence of a real fire and must not be affected by the presence of gases commonly found in the surrounding environment. The response must be quick, reliable, and able to provide relevant information to the crew.

In emissions monitoring applications, the detection of the chemical signature of the emissions of an engine may indicate the efficiency and health of the engine. Rapid or sudden changes in the emissions produced by combustion indicate changes in the engine combustion process. Further, the monitoring of emissions from chemical processing reactors or on-board experiments associated with Shuttle or International Space Station (ISS) operation can be used to provide early warning if a system is malfunctioning or to enhance the experiment.

The automotive industry has made significant progress in emissions reduction as well as monitoring the health of the catalytic converter by including oxygen sensors in the engine exhaust stream and using these sensors for combustion control. Ideally, an array of sensors placed in the emission stream close to the engine could provide information on the gases being emitted by the engine. However, there are very few sensors available commercially which are able to measure the components of the emissions in-situ in harsh environments such as an engine. The harsh conditions and high temperatures inherent near the reaction chamber of the engine render most sensors inoperable. The notable exception to this is, as mentioned above, the automotive oxygen sensor. Thus, in order to detect the other species present in an emissions stream, the development of new high temperature chemical sensor technology is necessary.

This paper discusses the point-contact sensor technology being developed to address the needs of leak, fire, and emission detection health monitoring applications. The development of these sensors is based on progress in three types of technology: 1) Micromachining and microfabrication (MEMS-based) technology to fabricate miniaturized sensors with minimal size, weight, and power consumption; 2) Fabrication of nanomaterials to create sensors with improved material properties; 3) The development of high temperature semiconductors, especially Silicon Carbide (SiC), to allow high temperature operation and detection of a range of chemical species.

A description is given of each sensor type and its present stage of development. A hydrogen sensor has been developed for launch vehicle applications that has a wide sensitivity range and can be combined with an oxygen sensor to allow detection of explosive conditions. This hydrogen sensor has been demonstrated on the Shuttle and chosen for use on the Hyper X (X-43), X-33, and International Space Station. A hydrocarbon fuel leak sensor is also under development to be combined with the hydrogen and oxygen sensors to create a complete fuel leak detection system. Fire detection sensors are being developed to complement existing smoke detection technology. At a minimum, the detection of CO and CO$_2$ are necessary for this application. Emission monitoring requires robust sensors that can withstand high temperature environments. Sensors to measure hydrogen (H$_2$), oxygen (O$_2$), nitrogen oxides (NO$_x$), CO, hydrocarbons (C$_x$H$_y$), and CO$_2$ are under development. A variety of these sensor technologies are presently being integrated to develop a High Temperature Electronic Nose that can measure a range of gases simultaneously. It is concluded that microfabricated chemical sensor technology has significant potential for use in a range of aerospace applications.

**SENSOR DEVELOPMENT**

**Hydrogen Sensor Technology**

In response to the hydrogen leak problems, NASA endeavored to improve propellant leak detection capabilities during assembly, pre-launch operations, and flight. In particular, efforts were made to develop an automated hydrogen leak detection system using point-contact hydrogen sensors. However, no commercial sensors existed at that time that operated satisfactorily in this and other space re-
lated applications. For example, commercially available sensors often needed oxygen or depended upon moisture to operate. Such sensors did not meet the needs of this application where hydrogen detection was necessary in inert environments or cryogenic environments. Thus the development of new sensor technology was necessary.

Two different hydrogen detection approaches are used depending on the concentration range. The detection of low concentrations of hydrogen involved using palladium (Pd) alloy Schottky diodes on a silicon substrate. This type of sensor is based on metal-oxide-semiconductor (MOS) technology such as that used in the semiconductor electronics industry. The gas sensing MOS structures are composed of a hydrogen-sensitive metal deposited on an oxide adherent to a semiconductor. This forms a Schottky diode in the case of a very thin layer of oxide (approximately 50 Å). The advantage of a Schottky diode sensing structure in gas sensing applications is its high sensitivity. Further, this type of sensor does not need oxygen for operation. If required, the detection of higher concentrations of hydrogen (up to 100%) is accomplished using a resistor whose resistance is dependent on the H₂ concentration.

The choice of the Pd alloy used in both the Schottky diode and resistor is critical for reliable sensor operation. The alloy chosen depends on the application. The use of pure Pd is problematic due predominately to a phase change that occurs at high hydrogen concentrations that can lead to hysteresis and/or film damage. The use of palladium silver (PdAg) has significant advantages for applications that do not require the exposure of the sensor to more than 1% hydrogen. However, the PdAg Schottky diode sensor response can drift if it is exposed to high hydrogen concentration at higher temperatures e.g., to 100% hydrogen at 100 °C. In contrast, palladium chrome (PdCr) has been shown to be responsive and stable over a wide range of hydrogen concentrations both in Schottky diode and resistor forms.

The design of the PdCr sensor is shown in Figure 1. The structure includes a Pd alloy Schottky diode and resistor, a temperature detector, and a heater all incorporated in the same chip. Also shown is a picture of the packaged sensor. The response of the Schottky diodes was determined by measuring the diode’s reverse current.

The sensor microfabrication allows the sensor package to have minimal size, weight, and power consumption and thus to be placed in a number of locations. Hardware and software (“Smart” electronics) have also been interfaced with the sensor to provide signal conditioning and control. The overall approach is to determine the magnitude and position of a leak in a region by correlating the signal from a number of these small sensor packages with electronics.

This complete hydrogen detection system (a two sensor chip with "Smart" electronics) has flown on the STS 95 mission of the Space Shuttle (launched 10-98) and again on STS 96 (launched 5-99). The hydrogen detection system was installed in the aft compartment of the Shuttle Orbiter and used to monitor the hydrogen concentration in that region. Presently, a mass spectrometer monitors the hydrogen concentration in the aft compartment before launch, while after launch "grab" bottles are used. Before flight, the inside of these "grab" bottles are at vacuum. During flight, the "grab" bottles are pyrotechnically opened for a brief period and the gas in the aft compartment is captured in the bottle. Several of these bottles are opened at different times during the takeoff and their contents are used to determine the time profile of the gases in the aft chamber. However, this information is only available after the flight.

![Figure 1](image)

Figure 1. a) Schematic diagram of the silicon-based hydrogen sensor. The Pd alloy Schottky diode (rectangular regions) resides symmetrically on either side of a heater and temperature detector. The Pd alloy resistor is included for high concentration measurements. b) Picture of the packaged sensor.
The data of the STS 95 mission has been analyzed. The response of the hydrogen sensors was compared to that of the mass spectrometer and those obtained by the "grab" bottles. During ground monitoring, the hydrogen sensor (Schottky diode) response was compared with that of the mass spectrometer during fueling (not shown). As fuel first entered the system, a small increase in hydrogen concentration was observed with both the hydrogen sensor and mass spectrometer. Overall, the hydrogen sensor response paralleled that of the mass spectrometer but with a larger signal and quicker response time perhaps due to the relative location of the sensor with respect to the hydrogen source.

The hydrogen sensor response during launch and in-flight is shown in Figure 2. No sensor response is seen until the cut-off of the main engine. Near this time, a spike in the hydrogen concentration is observed which decreases with time back to baseline levels. These results are qualitatively consistent with the leakage of very small concentrations of unburnt fuel from the engines into the aft compartment after engine cut-off. These observations also qualitatively agree with those derived from analyzing the contents of the grab bottles. Moreover, the advantage of this microsensor approach is that the monitoring of the aft compartment is continuous and, in principle, could be used for real-time health monitoring of the vehicle in flight.

![Figure 2. The response of PdCr Schottky diode sensor during the launch of the STS-95 Shuttle Mission.](image)

A second project where the MEMS-based hydrogen sensor technology is currently being applied is on the International Space Station. New technologies are being developed for the International Space Station regenerative life support system. One such system being developed by NASA for oxygen generation involves the electrolysis of reclaimed water. For this application a system consisting of triple redundant hydrogen sensors to monitor the product oxygen for trace hydrogen has been developed as a system safety monitoring sensor system. A prototype version of the sensor system is shown in Figure 3. For this application the sensors must be capable of detecting low concentrations of hydrogen (0 to 4%) in a pure oxygen background and relative humidity up to 100%. The sensors must have a fast response time (under 10 seconds) and have calibrations that are stable for several months to years. Engineering development versions of the sensors have been demonstrated for NASA and work is currently underway developing a flight-qualified version of the sensor system.

![Figure 3. Prototype, triple redundant hydrogen sensor system developed for use as part of the oxygen generator system for the International Space Station.](image)

The hydrogen sensors are also being used for trace hydrogen detection during flight operations for the X-43 (Hyper-X) program. For this application the sensors must operate in a variable pressure environment (0.1 to 1 atm) and be capable of producing an output signal displaying the total concentration of hydrogen. The background gas environment is inert. For this application, a pressure compensated version of the sensor system was developed that is capable of hydrogen concentration measurements (0 to 5%) at high altitude and with rapid transitions in altitude. The sensor was included on both the captive carry test (4-01) and first flight (6-01). Data from these missions will be published as available in a future publication.
Oxygen Detection

A microfabricated O₂ sensor is being developed based on electrochemical cell technology. Commercially available O₂ sensors are typically electrochemical cells using zirconium dioxide (ZrO₂) as a solid electrolyte and Pt as the anode and cathode. The anode is exposed to a reference gas (usually air) while the cathode is exposed to the gas to be detected. Zirconium dioxide becomes an ionic conductor of O₂ at temperatures of 600°C and above. This property of ZrO₂ to ionically conduct O₂ means that the electrochemical potential of the cell can be used to measure the ambient oxygen concentration at high temperatures. However, operation of these commercially available sensors in this potentiometric mode limits the range of oxygen detection. Further, the current manufacturing procedure of this sensor is relatively labor intensive, costly, and results in a complete sensor package with a power consumption on the order of several watts.

The objective of this research is to develop a zirconium dioxide solid electrolyte O₂ sensor using microfabrication and micromachining techniques. The combination of a fuel with O₂ produces a hazardous environment. Thus, the simultaneous measurement of both the fuel and O₂ is useful in leak detection applications. Also, the presence of O₂ often affects the response of H₂, CₓHᵧ, and NOₓ sensors. An accurate measurement of the O₂ concentration will help to quantify the response of other sensors in environments where the O₂ concentration is varying. Therefore, the combination of an O₂ sensor with other microfabricated gas sensors is envisioned to optimize the ability to detect fuel leaks and monitor emissions.

A schematic of the sensor structure is shown in Figure 4a). The microfabrication process allows the sensor to be small in size with low heat loss and minimal energy consumption. Energy consumption is further reduced by etching out the backside of the Si wafer so that the sensor components (temperature detector, heater, and sensing element) are over a diaphragm region. This minimizes the thermal mass of the sensing area thereby decreasing power consumption for heating and decreasing the time to reach thermal equilibrium. When operated in the amperometric mode, the current of this cell is a linear function of the ambient O₂ concentration. This linear response to oxygen concentration significantly increases the O₂ detection range of the sensor. A chamber structure with a well-defined orifice is micromachined to cover the sensing area. This orifice provides a pathway to control oxygen diffusion that is important in amperometric measurements as well as protection for the sensor. Figure 4b) shows a picture of the packaged sensor without its protective orifice. This basic design has been fabricated and tested. (See Hydrogen/Oxygen Sensor Array section below).

Figure 4. a) The structure of a microfabricated amperometric oxygen sensor. b) Picture of packaged sensor without its protective orifice.

NOₓ and CO Detection

Microfabricated and micromachined structures with a chemically sensitive resistor are being used to measure NOₓ and CO. The detection of NOₓ and CO is accomplished using nanocrystalline SnO₂ materials deposited on a microfabricated and micromachined substrate. The substrate can be either Si or ceramic. Figure 5 shows the basic structure of the sensor design using a Si substrate: it consists of two components (Si and glass) that are fabricated separately and then bonded together. The microfabrication process allows the sensor to be small in size with low heat loss and minimal energy consumption. Energy consumption is further reduced by depositing the sensor components (temperature detector, heater, and sensing element) over a diaphragm region. This minimizes the thermal mass of the sensing area thereby decreasing power consumption for heating and decreasing the time to reach thermal equilibrium. The substrate utilized
for the Si-based design is a 0.15 mm thick glass. On one side of the glass are formed the heater and temperature detector, and on the other side are sputtered platinum interdigitated fingers. The width of the fingers and the gap between them is 30 μm each. The overall sensor dimensions are approximately 300 microns on a side with a height of 250 microns. Figure 6 shows the picture for an assembled sensor. The advantage of this design is its minimal power consumption that is near 80 mW for several hundred degrees centigrade of heating.

![Diagram of SnO$_2$ sensor](image.png)

Figure 5. Structure of a SnO$_2$ based sensor on a Si substrate. The sensor has Si and glass component and includes a temperature detector and heater.

The sensing element is composed of interdigitated electrode elements across which is deposited SnO$_2$. Changes in conductivity of doped SnO$_2$ across the interdigitated electrodes is measured and correlated to NO$_x$ or CO concentration. A major component of this development work is to stabilize the SnO$_2$ for long-term, high temperature operation. Drift in the properties of SnO$_2$ with long term heating due to grain boundary annealing have been previously noted$^{8,9}$. This drift results in changes in the sensor output with time and reduces sensor sensitivity. In order to stabilize the SnO$_2$ grain structure for long-term operation, the fabrication of nanocrystalline SnO$_2$ is being investigated. Nanocrystalline materials have several inherent advantages over conventionally fabricated materials including increased stability and sensitivity at high temperature$^{10,11}$.

A nanocrystalline SnO$_2$ based NO$_x$ sensor has been tested in a power generation turbine engine$^{12}$ as well as part of an array. This sensor was fabricated on an alumina substrate (not shown) and placed in a region where the flow stream from the engine is extracted and passed over the sensor. Nanocrystalline SnO$_2$ sensors (with different doping) have also shown high sensitivity to CO$^{13}$. The nanocrystalline tin oxide sensors were also tested as part of an array of gas sensors as discussed in the High Temperature Electronic Nose section below.

![Image of SnO$_2$ sensor mounted in ceramic flat package](image.png)

Figure 6. Microfabricated SnO$_2$ sensor mounted in ceramic flat package.

**Hydrocarbon Detection**

The development of hydrocarbon sensors for use in harsh environments has centered on the development of a stable SiC-based Schottky diode. The advantage of SiC over Si is its ability to operate as a semiconductor at temperatures in excess of 600°C. This allows SiC-based gas sensors to operate at temperatures high enough to allow the detection of hydrocarbons$^{14}$. The first SiC-based Schottky diode structure developed at NASA Glenn Research Center (GRC) was Pd on SiC MS structures (Pd/SiC). Direct contact between the catalytic metal and the semiconductor allows changes in the catalytic metal to have maximum effect on the metal-semiconductor electronic properties. Studies of this baseline system help to determine the limits of diode sensitivity, potential material interactions between Pd and SiC, and whether a barrier layer between the Pd and SiC is necessary for long-term sensor stability. The sensor detects C$_x$H$_y$ in inert or oxygen-containing environments. The details of this work are reviewed elsewhere$^{14}$.

The Pd/SiC sensor response is affected by extended high temperature heating. Prolonged heating at 425°C has been shown to change the sensor properties and to decrease sensor sensitivity$^{14}$. The reason for this change in diode properties is likely due to reactions between the Pd and SiC interface upon heating.
Efforts have been underway to stabilize the sensor structure for long-term, high temperature operation. Two new structures have been demonstrated which improve the stability of the Pd-based Schottky diode structure over that of Pd/SiC. These structures involve: 1) The use of an alloy as the catalytic metal. 2) The use of a metal-insulator-semiconductor (MIS) structure where the “insulator” stabilizes the interface and is also reactive to the gases of interest. Preliminary testing of both of these structures suggests significantly improved stability and response over Pd/SiC.

**CO₂ Detection**

There are two approaches to the detection of CO₂. The first approach is based on the use of a solid electrolyte as in the detection of oxygen. The significant difference from the O₂ sensor is the use of NASICON (sodium super ionic conductor) as the solid electrolyte. NASICON is an ionic conductor composed of Na₃Zr₂Si₂PO₈. The sensor structure will be similar to that of Figure 4: a microfabricated electrochemical cell with integrated temperature control. The second approach is based on the doping of nanocrystalline SnO₂ for improved CO₂ sensitivity. With either approach, the overall objective is to produce a microfabricated sensor that can be incorporated with other sensors such as the CO sensor into a single unit. A combined CO₂/CO sensor is of interest not only for fire safety applications but for combustion monitoring applications as well.

**SENSOR ARRAYS**

**Hydrogen/Oxygen Sensor Array**

The development of miniaturized chemical sensor microsystems using the hydrogen and oxygen sensor elements combined in one package is currently underway. A prototype MEMS-based leak detection sensor system has integrated both hydrogen and oxygen sensors into a single substrate and realized improvements in the hardware supporting the sensor array. The size of the electronics is determined, in part, by the requirements of the aerospace application. For space based applications, electronics must often meet military specifications, be radiation hard, or must function on vehicle voltage supplies that are not optimized for small scale electronics (e.g. 28 V rather than 5 V). The smallest, most powerful electronics may not meet these specifications or a bulky transformer may have to be added to the system to accommodate power restrictions.

The results of efforts to decrease the size of the system with associated electronics is shown in Figure 7 which shows a prototype of an existing system: two sensors, hydrogen and oxygen, are integrated on the same board as the “smart” electronics. The smart sensor package contains all required analog and digital electronics, including CPU, memory, and communications devices. The total volume of the package is less than 5 cm³. The supporting electronics have been chosen for flight readiness while other components are still in the process of being qualified.

![H2 SENSOR](image)

![O2 SENSOR](image)

**Figure 7.** Prototype miniature smart sensor with combined hydrogen and oxygen sensors with control electronics.

The operation of the prototype sensor unit with combined hydrogen and oxygen sensors is shown in Figure 8. The response to changes in gas concentrations of the two hydrogen sensing elements (a hydrogen sensitive resistor and Schottky diode) as well as an oxygen sensor is shown. In a nitrogen ambient, all 3 sensors are first exposed to 21% O₂ and the concentration of hydrogen is varied from 0% to a maximum of 1.5% and back to 0%. Then the oxygen background is changed from 21% to 4% O₂ and the hydrogen concentration stepwise increased and then decreased through the same hydrogen concentration range (0% to 1.5%). The hydrogen sensitive resistor provides higher sensitivity at higher hydrogen concentrations while the Schottky diode provides a larger response at lower hydrogen concentrations. The O₂ concentration is measured independently.

The combined responses from both the H₂ and O₂ sensors are a powerful tool for leak detection. Since the H₂ sensor response weakly depends on the O₂ concentration, the O₂ signal can be used to more accurately determine the H₂ concentration. More importantly, since the LEL of the combustible gas depends, in part, on the corresponding concen-
tration of the oxidizer, knowing the relative ratio of the gases is necessary to determine if an explosive condition exists. Using the sensor system shown in Figure 7, information is provided on both the concentration of the combustible gas (H₂) and the oxidizer (O₂) simultaneously and thus a more accurate determination of the hazardous conditions can be determined.

This work demonstrates the beneficial use of multiple sensors with different detection mechanisms yielding improved information about the chemical constituents of an environment. It is envisioned that this multiple microsensor approach, combined with MEMS-based fabrication of the component parts, can allow the placement of sensors in a number of locations to better determine the safety of the region of interest. The long-term objectives of this work in the Second Generation Spaceliner program is to produce a fuel/oxygen sensor array with the surface area of postage stamp which includes the power and communications support structure to make it a stand-alone system. The fuel of this Second Generation vehicle could be hydrogen or hydrocarbon based; therefore both hydrogen and hydrocarbon detection are necessary. Combined with an oxygen sensor, this complete system can have the ability to detect fuel leaks with the corresponding oxygen level from a wide range of propulsion systems.

Further, in order to have a postage stamp sized system increased miniaturization of the existing microfabricated technology is necessary. This work has begun as seen in Figure 9. Figure 9 shows the oxygen sensor design of Figure 4 compared to a new, smaller version of the sensor. This new design is expected to have capabilities of the present design but also significantly reducing the size and power consumption.

Figure 8. The response of a hydrogen (2 sensors) and oxygen detection system with associated electronics to multiple concentrations of hydrogen in a changing oxygen ambient.

Figure 9. Comparison of the size of two oxygen sensors produced using different processing approaches. A smaller sensor size with less power consumption is necessary for integrated, postage-stamp sized sensor systems envisioned for the next generation of vehicles.

Fire Detection Array

The detection of CO and CO₂ are two of the major chemical species produced with the onset of most fires. While the presence of other species (such as hydrocarbons) are of interest, significant chemical species information regarding the indication of a fire can be obtained by measuring the ratio of concentrations of CO to CO₂ as well as their rate of change.

Efforts are under way to produce a CO/CO₂ detector on a chip. Figure 10 shows an early version of the sensor based on SnO₂ used to detect both CO and CO₂ with different doping used to improve selectivity. Figure 10a shows the relative dimensions of the sensor while Figure 10b show a magnified view of the two sensors. An indentation in the sensor area in Figure 10b is due the diaphragm under the sensors formed with micromachining. Testing of this and other combined CO/CO₂ sensor combination continues. The major technical issues revolve around processing of the CO₂ sensor. These include deposition problems associated with the NASICON based CO₂ sensor and selectivity issues for the SnO₂ based CO₂ sensor.
High Temperature Electronic Nose

Integration of a number of the individual high temperature gas sensors discussed in this paper could detect $H_2$, $O_2$, $NO_x$, $CO$, $C_{x}H_{y}$, and $CO_2$. Development of a such a microfabricated gas sensor array operable at high temperatures and high flow rates would be a dramatic step towards realizing the goal of monitoring/control of emissions produced by an engine, a power generation unit, or a chemical reactor. Such a gas sensor array would, in effect, be a high temperature electronic nose and be able to detect a variety of gases of interest. Several of these arrays could be placed around the exit of the engine exhaust to monitor the emissions produced by the engine. The signals produced by this nose could be analyzed to determine the constituents of the emission stream and this information then could be used to monitor the health of the system producing those emissions.

The concept of an electronic nose has been in existence for a number of years. Commercial electronic noses for near-room temperature applications presently exist and there are a number of efforts to develop other electronic noses. However, these electronic noses often depend significantly on the use of polymers and other lower temperature materials to detect the gases of interest. These polymers are generally unstable above 400°C and thus would not be appropriate for use in harsh engine environments. Thus, a separate development is necessary for a High Temperature Electronic Nose.

The development of such a High Temperature Electronic Nose has begun using the high temperature sensors discussed in this paper. In addition to the higher temperature limit of the sensors that constitute this Nose, there are three very different sensor types that constitute the High Temperature Electronic Nose: resistors, electrochemical cells, and Schottky diodes. Each sensor type provides qualitatively very different types of information on the environment. This is in contrast to a conventional array of sensors that generally consists of elements of the same type, e.g. $SnO_2$ resistors doped differently for different selectivities. Each sensor in this conventional system provides information available through the differently doped $SnO_2$ resistors (reactions occurring on the surface of the sensor film) but do not provide information determined by electrochemical cells or Schottky diodes. It is envisioned that the elements of the High Temperature Electronic Nose array (resistors, diodes, and electrochemical cells) will have very different responses to the individual gases in the environment. This information will be integrated and interpreted using neural net processing to allow a more accurate determination of the chemical constituents of harsh, high temperature environments.

A first generation High Temperature Electronic Nose has been demonstrated on a modified American Institute of Aeronautics and Astronautics
The figure shows the response of the oxygen sensor, and a SiC-based hydrocarbon sensor. The figure shows the individual sensor responses during the initial start of the engine, a warm-up period, a steady state operation period, and at the engine turn-off. The sensors were operated at 400 °C while the engine operating temperature was 337 °C. Each sensor has a different characteristic response. The oxygen sensor shows a decrease in O$_2$ concentration while the NO$_x$ and C$_y$H$_x$ concentrations increase at start-up. The hydrocarbon concentrations decrease as the engine warms up to steady-state while the NO$_x$ concentration increases before stabilizing. The O$_2$, NO$_x$, and C$_y$H$_x$ concentrations all return to their start-up values after the engine is turned off. These results are qualitatively consistent with what would be expected for this type of engine. They also show the value of using sensors with very different response mechanisms in an electronic nose array: the information provided by each sensor was unique and monitored a different aspect of the engine’s chemical behavior.

HEALTH MONITORING AND MANAGEMENT APPLICATIONS

The long-term development of smart propulsion systems and vehicles would include the monitoring of the chemical properties of subcomponents of these systems. The gas sensor technology being developed in this program is a significant step in that direction. These sensors have the capability to measure many of the gases important in health monitoring and management even beyond those discussed in this paper. This can be accomplished by using the three types of sensor platforms being developed in this work: Schottky diodes, resistors, and electrochemical cells. Using these platforms, the sensors being developed would measure standard gases that are present in throughout aerospace applications: H$_2$, C$_x$H$_y$, NO$_x$, CO, O$_2$ and CO$_2$. However, by modifying, for example, the gas selective resistor material, a different sensitivity to a given gas can be achieved allowing a further expansion of the detection capabilities of this microfabricated technology.

As discussed above, this gas sensor technology will allow the determination of the safety and health of the system by, for example, detecting leaks which could lead to explosions, the presence of a fire, or the condition of engine as determined by the emissions. Integrating such sensor technology into an overall Vehicle Health Monitoring and Management system is a long-term objective of the NASA GRC Chemical Sensors program. This long-term objective can met by tailoring an array of sensors for the specific application and combining them with smart electronics and signal conditioning (as is being developed for leak detection). The addition of signal analyzing software to the system to interpret sensor responses (as is being done in the High Temperature Electronic Nose program) will enable determination of the chemical condition at the location of the sensor system. Miniaturization of the entire sensor system (sensor array, signal conditioning, and electronics) and locating many of these sensor systems throughout a region of interest will allow autonomous monitoring nodes which can determine the health of a given vehicle subcomponent.

SUMMARY

The needs of aerospace vehicle health management applications require the development of gas sensors with capabilities beyond those of commercial sensors. These requirements include operation in harsh environments, high sensitivity, as well as minimal size weight and power consumption. Sensor technology is being developed to address these requirements using microfabrication and micromachining technology, nanomaterials, and SiC semiconductor technology. Several types of sensors have been described which have space vehicle monitoring applications. Some of the sensor designs are relatively mature while the development of others is ongoing. The combination of these technologies may allow the development of complex chemical analysis for health monitoring and management in smart vehicles.

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