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# Microfabricated Hydrogen Sensor Technology for Aerospace and Commercial Applications

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ABSTRACT

Leaks on the Space Shuttle while on the Launch Pad have generated interest in hydrogen leak monitoring technology. An effective leak monitoring system requires reliable hydrogen sensors, hardware, and software to monitor the sensors. The system should process the sensor outputs and provide real-time leak monitoring information to the operator. This paper discusses the progress in developing such a complete leak monitoring system.

Advanced microfabricated hydrogen sensors are being fabricated at Case Western Reserve University (CWRU) and tested at NASA Lewis Research Center (LeRC) and Gencorp Aerojet (Aerojet). Changes in the hydrogen concentrations are detected using a PdAg on silicon Schottky diode structure. Sensor temperature control is achieved with a temperature sensor and heater fabricated onto the sensor chip. Results of the characterization of these sensors are presented. These sensors can detect low concentrations of hydrogen in inert environments with high sensitivity and quick response time. Aerojet is developing the hardware and software for a multipoint leak monitoring system designed to provide leak source and magnitude information in real time. The monitoring system processes data from the hydrogen sensors and presents the operator with a visual indication of the leak location and magnitude.

Work has commenced on integrating the NASA LeRC-CWRU hydrogen sensors with the Aerojet designed monitoring system. Although the leak monitoring system was designed for hydrogen propulsion systems, the possible applications of this monitoring system are wide ranged. Possible commercialization of the system will also be discussed.

1. INTRODUCTION

In the rocket propulsion industry, hydrogen propellant leaks pose significant operational problems. In spite of large efforts to find and correct leaks in assembly and test, launch operations continue to be impacted by hydrogen leaks. In 1990, the leaks on the Space Shuttle while on the launch pad temporarily grounded the fleet until the leak source could be identified. In response to the hydrogen leak problem, several initiatives have been undertaken by NASA to improve propellant leak detection capabilities during assembly, pre-launch operations, and flight. The objective has been to reduce the operational cost of assembling and maintaining hydrogen delivery systems with automated detection systems. In particular, efforts were made to develop an automated hydrogen leak detection system using microfabricated point-contact

hydrogen sensors.

The development of such an automated hydrogen detection system requires both dependable hydrogen sensors and the hardware and software to monitor the hydrogen sensors. Efforts have progressed on two fronts. NASA Lewis Research Center (LeRC), in conjunction with Case Western Reserve University (CWRU), is developing point-contact hydrogen sensors. These sensors are microfabricated to minimize power consumption and allow placement in a wide variety of locations. In a separate contract with Marshall Space Flight Center (MSFC), Gencorp Aerojet (Aerojet) is developing an automated hydrogen leak detection system that monitors microfabricated point-contact hydrogen sensors and visually displays the source of a leak. The combined effort of these two programs is a complete system that can monitor leaks in hydrogen propulsion systems.

The complete system consists of three elements: a sensor array, a signal processing unit, and a diagnostic processor. The sensor array consists of discrete microfabricated hydrogen sensors which are located in potential leak sites. The signal processing unit provides power to the sensors and analog to digital data conversion of the sensor outputs. The diagnostic processor analyzes the sensor outputs to determine leak source positions and magnitude. Leak data from the sensor network is interpreted using knowledge based software and displayed on-line through a graphical user interface including 3-D leak visualization. The system requirements have been developed for application to the Space Shuttle Main Engine which requires approximately 72 measurement locations.

Hydrogen propulsion system monitoring is not the only application that could make use of a leak detection system. The monitoring system described in this paper could be used with any vehicle or facility using gaseous hydrogen. The present commercial chemical and food industries are also heavy users of hydrogen. The acceptability of exotic technologies such as battery or hydrogen powered transportation systems depends on finding ways to maintain safety in day to day operations. Aerojet is presently pursuing commercialization of this technology that will use the hydrogen sensors developed at NASA LeRC and CWRU in a number of applications.

The purpose of this paper is to discuss the development of the hydrogen leak detection system. The first section will discuss the development of microfabricated hydrogen sensors at NASA LeRC and CWRU. The next section will discuss the hardware, sensor integration, and software in the Aerojet system. The following section will discuss the prototype multiplexing system developed at Aerojet. It is demonstrated that this effort represents significant interaction between NASA, industry and academia. Future commercial development plans will also be discussed.

## 2. HYDROGEN SENSORS DEVELOPMENT

The development of present design of the hydrogen sensor was a collaborative effort between NASA LeRC and CWRU. The sensors were fabricated at CWRU and characterized at NASA LeRC. The results of this characterization affected future sensor fabrication procedure. Through this collaboration between government and academia, an improved sensor design has been developed. The following discusses the NASA LeRC Hydrogen Sensor Testing System used to characterize the sensors and the hydrogen sensor design.

### 2.1 Hydrogen Sensor Testing System

The facility used for sensor testing at NASA LeRC is shown schematically in Figure 1. The facility can supply a continuous flow of gaseous hydrogen, helium, nitrogen, or air, either individually or as a mixture, to a chamber containing the sensor under test. The temperature and pressure of gas are measured as the gas enters the test chamber. The composition of the gas is monitored by a mass spectrometer. The gas leaves the test chamber and is sent through a flame before being vented.

Computer-controlled mass flow controllers give a continuous gas flow at a range of flow rates. A flowing system is used since it is assumed that leaking hydrogen would come from a pressurized system resulting in streams of hydrogen. The helium, nitrogen, air, and one hydrogen mass flow controller are calibrated for flows from 0 to 1000 standard cubic centimeters per minute (sccm). A second hydrogen mass flow controller is calibrated for 0 to 20 sccm flows. A three-way valve allows the gas to bypass the test chamber and go directly to the vent. This feature allows the mass flow controllers to be stabilized without flowing gases through the test chamber.

The mass flow controllers can also flow gases for which they are not calibrated. Thus, a given gas can be flowed through more than one mass flow controller to increase the overall flow rate of that gas. Further, gas mixtures such as 1% hydrogen in nitrogen can also be used. Determination of the true flow rate when flowing alternate gases through a given mass flow controller is obtained by using manufacturer provided conversion factors. This system allows a wide range of hydrogen containing mixtures to be sent through the test chamber at a wide range of flow rates. The test chamber is designed for testing of several sensors which are mounted on DIP connectors. The incoming gas is injected on to the sample surface by means of a tube conducting the gas into the chamber.

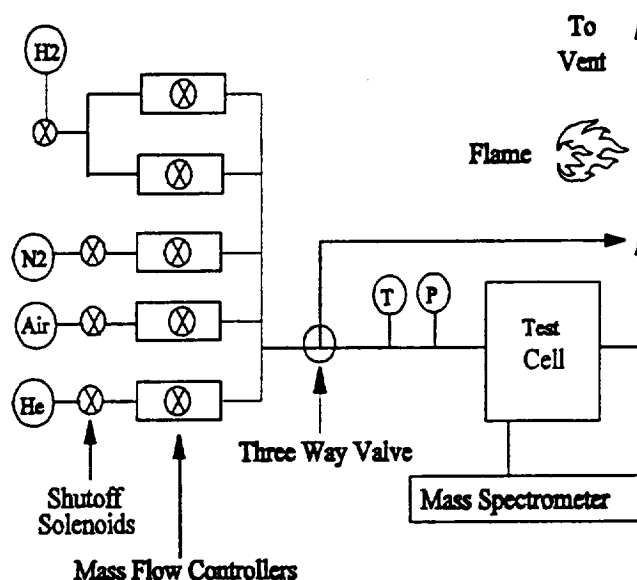


Figure 1. Schematic diagram of the NASA LeRC  $H_2$  sensor testing facility. T and P represent temperature and pressure measurements.

The mass spectrometer provides an independent measure of the relative concentration of the gases in the test cells as a function of time. This information, accounting for the time delay inherent in the mass spectrometer reading, has been used to determine the amount of time for changes in the flow composition to reach a steady state value in the test chamber. The time it takes to reach steady state affects the corresponding measured response and recovery times of the sensor. On the basis of this information, testing procedures sought to maximize the flow rate and thereby minimize the time for the test chamber to reach steady state. Thus, the total flow rates used in the tests discussed in this paper are maximized within the constraints of the available gases and mass flow controllers. The flow rates for the tests at NASA LeRC were 1500 sccm. Under these conditions, the time for steady state in the multisensor chamber is usually less than a minute.

## 2.2 Hydrogen Sensor Fabrication and Characterization

The development of microfabricated hydrogen sensors was necessary since hydrogen sensors that meet the needs of aerospace applications did not exist<sup>1-2</sup>. One component the sensor development program at NASA LeRC involves the fabrication at CWRU of palladium-silver (PdAg) Schottky diodes on silicon (Si) substrates. 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 insulator adherent to a semiconductor. This forms a Schottky diode in the case of a very thin layer of insulator. The most common MOS structure used for hydrogen detection is the Pd-SiO<sub>2</sub>-Si structure. Hydrogen disassociates on the Pd surface and diffuses to the Pd-SiO<sub>2</sub> interface affecting the electronic properties of the MOS system<sup>3</sup>. The use of pure Pd as the hydrogen sensitive metal is problematic for several reasons. The most serious of these involves a phase change that occurs at high hydrogen concentrations which can lead to hysteresis or film damage.

Schottky diodes using Pd13%Ag as the hydrogen sensitive metal are presently being fabricated. The use of PdAg in

hydrogen sensing applications was pioneered by Hughes<sup>4</sup>. Palladium silver has advantages over Pd. Palladium silver is more resistant to damage from exposure to high hydrogen concentration than Pd. Furthermore, the alloy has faster response times than Pd. The 13% Ag concentration is the optimum concentration for balancing these improved properties and the need to have a large enough Pd concentration to allow sensitivity to hydrogen<sup>5</sup>.

The sensor structure is shown in Figure 2. The structure includes a Pd13%Ag Schottky diode, a temperature detector, and a heater all incorporated in the same chip. The sensor is fabricated using a n-type silicon wafer on which approximately 50 Å of SiO<sub>2</sub> is thermally grown in the sensor region. The heater and temperature detector are platinum covered with SiO<sub>2</sub>. Gold leads are applied by thermal compression bonding and the sensor is mounted on a TO5 header or on a ceramic flat package. The surface area of the Schottky diode is  $6.1 \times 10^{-3} \text{ cm}^2$ .

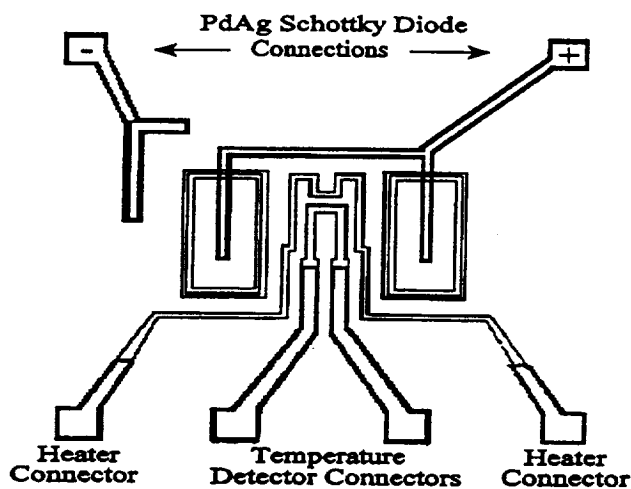


Figure 2. Schematic diagram of the Pd13%Ag Schottky Diode Hydrogen Sensor. The Pd13%Ag Schottky diode resides symmetrically on either side of a heater and temperature detector.

The response of the Schottky diodes was determined by measuring the diode's reverse current. Five volts were placed across a circuit composed of the diode and a separate resistor in series. The reverse current was determined by measuring the voltage drop across the resistor. The sensor temperature was measured from the resistance of the temperature detector in a Wheatstone bridge.

The time response of a typical Pd13%Ag Schottky diode sensor at a sensor temperature of 45 °C to 0.2% hydrogen is shown in Figure 3. Two different experiments using two different carrier gases are shown: either pure nitrogen or a mixture of 90% N<sub>2</sub> and 10% O<sub>2</sub>. The sensor is first exposed to the carrier gas for 10 minutes, then to 0.2% H<sub>2</sub> in the carrier gas, then the carrier gas. This is done for 4 cycles. After the last exposure to hydrogen, the nitrogen carrier gas is changed to the 90% N<sub>2</sub>:10% O<sub>2</sub> mixture.

Several features of the sensor behavior should be noted. First, the sensor is highly sensitive to hydrogen with a rapid response to hydrogen introduction in either an inert or an oxygen containing carrier gas. The reverse current increases by nearly 1000 when the sensor is exposed to hydrogen, from on the order of 0.1 μA to on the order 100 μA. The measured response time is chamber dependent. Our data suggests the response time under these conditions is less than 45 seconds to reach 90% of the final value.

Secondly, the presence of oxygen significantly affects the sensor behavior. The sensor response to nitrogen is more than a factor of two larger than that in nitrogen and oxygen. The presence of oxygen also impacts the recovery time. The recovery time to 90% of the baseline value in nitrogen and oxygen is on the order of seconds, while the recovery time in pure nitrogen is on the order of many minutes. However, when the carrier gas is changed from nitrogen to the nitrogen and oxygen mixture at time equal to 80 minutes in Figure 3, the sensor recovers with approximately the same speed as found

when the carrier gas contains oxygen.

Thirdly, Figure 3 demonstrates the repeatability of the sensor response. For each exposure to hydrogen, the reverse current increases to within 13% of the same value. It should be noted that this 13% variation is out of a total change of near 1000 for both gas mixtures. Further, even the pattern of the slow recovery in nitrogen is repeatable.

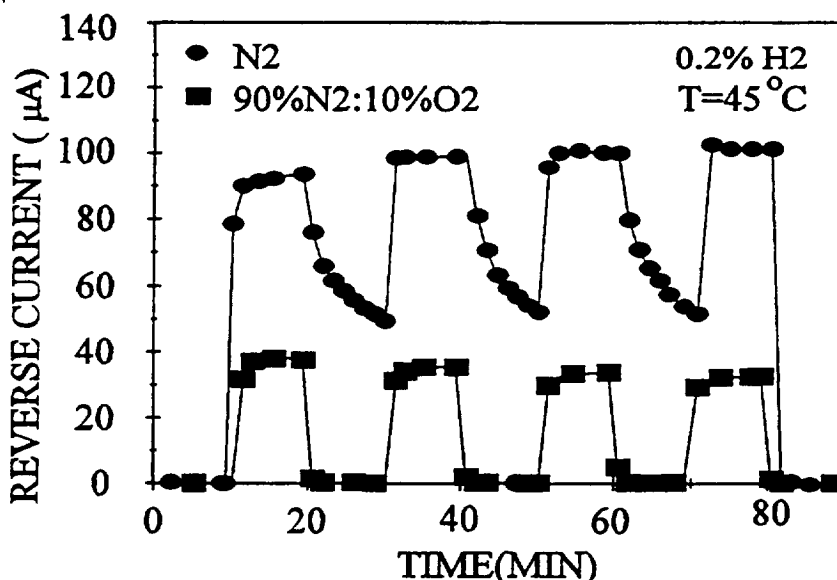


Figure 3. The time response of a Pd13%Ag Schottky diode hydrogen sensor to cycling to 0.2% hydrogen in N<sub>2</sub> and 90% N<sub>2</sub> and 10% O<sub>2</sub>. The large and rapid response of the sensor and the effect of oxygen is evident.

The response of the sensor to varying temperatures and hydrogen concentrations in a 90% N<sub>2</sub>:10% O<sub>2</sub> carrier gas is shown in Figure 4. The sensor temperatures tested were 45°C, 60°C, 80°C, and 100°C. The sensor was first exposed to the carrier gas for 10 minutes, then, for 10 minutes each, 100 ppm, 500 ppm, 1000 ppm, and 5000 ppm H<sub>2</sub> in the carrier gas. The hydrogen flow was then stopped and the sensor recovered towards the baseline in the carrier gas. Figure 4 shows the sensor response on a linear scale, while the inset shows the first 30 minutes of the same test on a logarithmic scale.

The first sensor characteristic demonstrated by Figure 4 concerns the magnitude of the response of the diode throughout the temperature and hydrogen concentration range. After a response of nearly an order of magnitude to 100 ppm H<sub>2</sub> (Figure 4 inset), the sensor responds by a factor of nearly 100 to the subsequent factor of 50 change in the hydrogen concentration (Figure 4). Therefore, the sensor reverse current responds to changes in hydrogen concentration throughout the hydrogen concentration range from 100 ppm to 5000 ppm in air and for sensor temperatures below 100°C.

Secondly, the magnitude of the response and the time it takes for the sensor to reach a stable value is temperature dependent. The higher the temperature, the larger the reverse current and the shorter the time until the reverse current stabilizes. However, the sensor response at 100°C and 5000 ppm hydrogen concentration is different from that at other temperatures. The reverse current reaches a maximum almost immediately upon the change from 1000 ppm to 5000 ppm hydrogen, then decreases with continued hydrogen exposure. This high concentration/high temperature behavior is explored further elsewhere<sup>6</sup>.

Therefore, the properties of the Pd13%Ag sensor make it very useful for applications where sensing small amounts of hydrogen is necessary. The sensor response is large, rapid, and repeatable. If quick recovery is necessary, then the sensor should be operated in oxygen containing gases. If detection of the presence of hydrogen is required without rapid recovery, then this sensor can also be used in inert environments. The sensor responds to hydrogen across a wide concentration range with a signal and response time that is temperature dependent. This sensor can be used to monitor leaks in a multipoint leak

detection scheme involving a number of these sensors. The design of the Aerojet produced system to monitor these and possibly other sensors follows in the next section

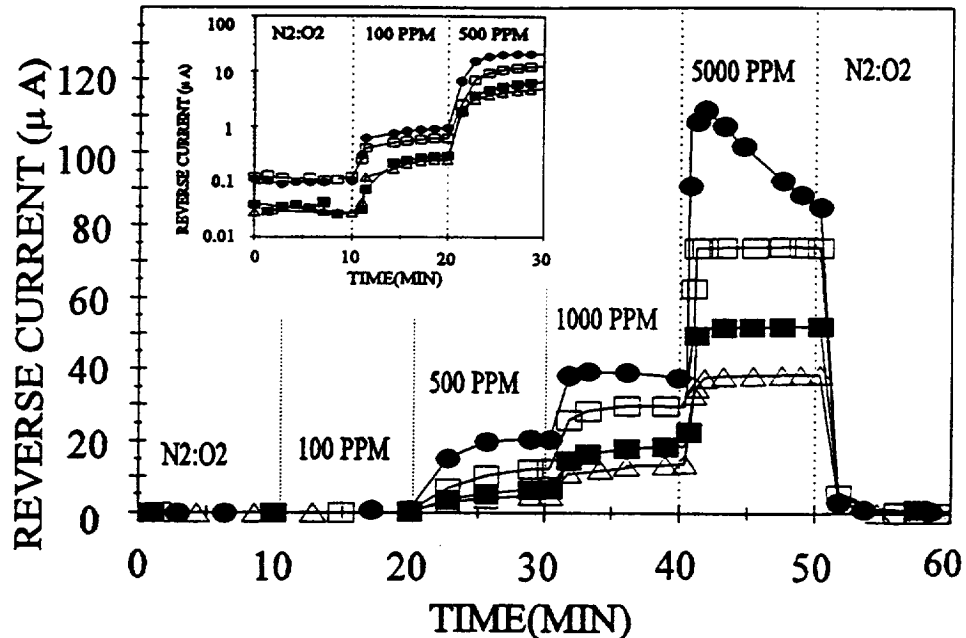


Figure 4. The response of a Pd13% Ag hydrogen sensor as a function of temperature when exposed for 10 minutes to the carrier gas 90% N<sub>2</sub>:10% O<sub>2</sub>, and then for 10 minutes each to 100 ppm, 500 ppm, 1000 ppm, and 5000 ppm of H<sub>2</sub> in the carrier gas. The inset shows the carrier gas, 100 ppm and 500 ppm response in a logarithmic scale. The temperatures are 45°C (Δ), 60°C (■), 80°C (□), and 100°C (●).

### 3. MULTIPOINT LEAK DETECTION MONITORING

In order to gain information from a large number of the sensors in actual field applications, hardware and software must be available to operate the sensors and interpret the incoming data. The sensor support structure design must take into account the needs of aerospace applications. For example, the amount wiring and power used to operate the sensors must be kept at a minimum. The signal from the sensors must be processed and displayed by the hardware and software in such a manner so as to be useful to the operator. Aerojet has been actively involved in developing such a system. The goal of the automated hydrogen propellant leak detection system is to provide leak source and magnitude information in real time. The following subsection presents the system hardware design and sensor integration. The second subsection discusses the leak detection software and algorithms.

#### 3.1 Hardware Design and Sensor Integration

The major design features of the automated hydrogen propellant leak detection system is illustrated in Figure 5. The hydrogen sensors provide electrical signals that indicate the local hydrogen partial pressure. These sensors are distributed throughout the propulsion system fuel tanks, feedlines, and engine elements. Individual sensors, characterized as site sensors, are located at high probability leak sources such as flanges, instrumentation ports or in areas with limited physical or visual access. Other sensors are mounted throughout the engine and flowline compartments providing zone-imaging data serving as safety monitors.

Development of a distributed array leak detection system requires connecting and gathering information from a large number of sensors. Mounting a large number of point sensors throughout the leak susceptible area poses a significant cabling



challenge. Each device must be provided with connections for heating power, device bias voltages, temperature sensing, and one or more hydrogen sensors. The cost of cabling to large number of active sensor elements that a practical system would employ is reduced by multiplexing a string of sensors into a single cable, terminating several cables at each distributed signal processor, and connecting the signal processors with the ground data processor through a single serial bus. Making use of the increasing integration that the electronics industry is providing in monolithic micro-controllers, the signal processor units are expected to be small units mounted in proximity to the sensors throughout the vehicle and launch pad fuel delivery systems. The distributed signal processors collect, process, and record the sensor measurements. Once the data is collected, it is serialized and transmitted to a ground based data processor where the leak detection algorithms are executed.

The degree to which the leak detection can successfully identify and characterize leaks depends on how reliably the instantaneous local hydrogen content can be inferred from the point hydrogen sensor signals. Device to device variations and saturation level must be considered. In order to characterize the behavior of a number of sensors in a multiplexing scheme, several sensors were tested. Figure 6 shows time plots of the reverse biased diode currents for eight multiplexed sensors responding to and recovering from exposure to various hydrogen/nitrogen mixtures. The testing was done at Aerojet in a smaller test chamber than the LeRC system but with flow control similar to that seen in Figure 1. The measurement is output signal after signal conditioning. The measurements show that the characteristic responses times of these devices are less than 10 seconds. The steady state level of response corresponds to the hydrogen concentration at exposure except when saturation occurs which is approximately 1% hydrogen.

Figure 7 shows typical calibration cross plots derived from the data shown in Figure 6. The value of the measurement at 1000 ppm hydrogen in nitrogen is set to 1 and all other measurements are normalized to this value. The sensors have similar calibration curves over the range of concentrations from 50 PPM to 1% hydrogen. The similarity of the calibration curves is important since this means that processing of the sensor array response will only require a limited number of corrections constants for each sensor rather than wholesale calibration curves for each sensor.

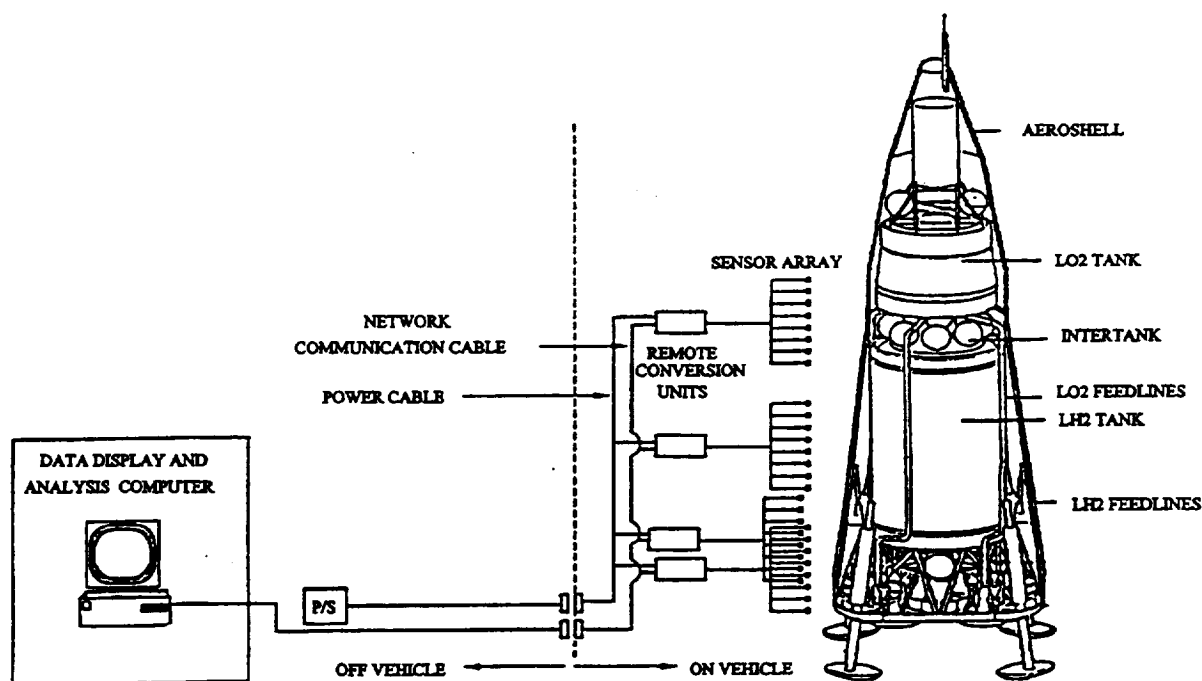


Figure 5. Schematic of Automated Leak Detection System for Propulsion Systems. The system monitors hydrogen leaks at points of interest throughout the vehicle using hydrogen sensors monitored by advanced hardware and software.

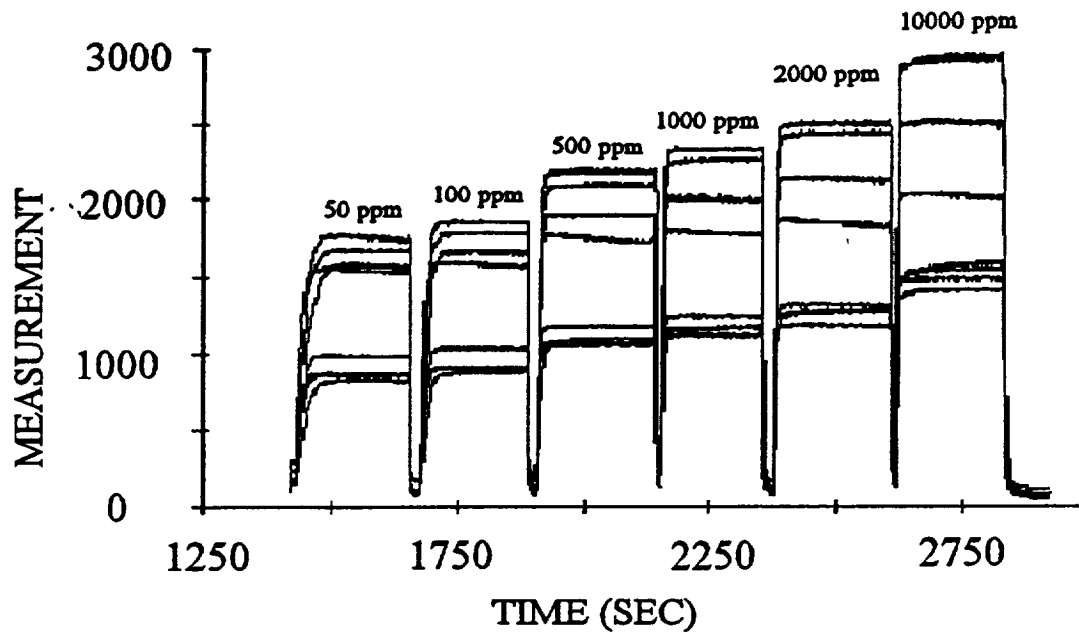


Figure 6. Characteristic step response of the hydrogen sensors in a multiplexed system. The measurement is the response of the sensor after signal conditioning. The gas flow is hydrogen in nitrogen and the sensor temperature is 60 °C.

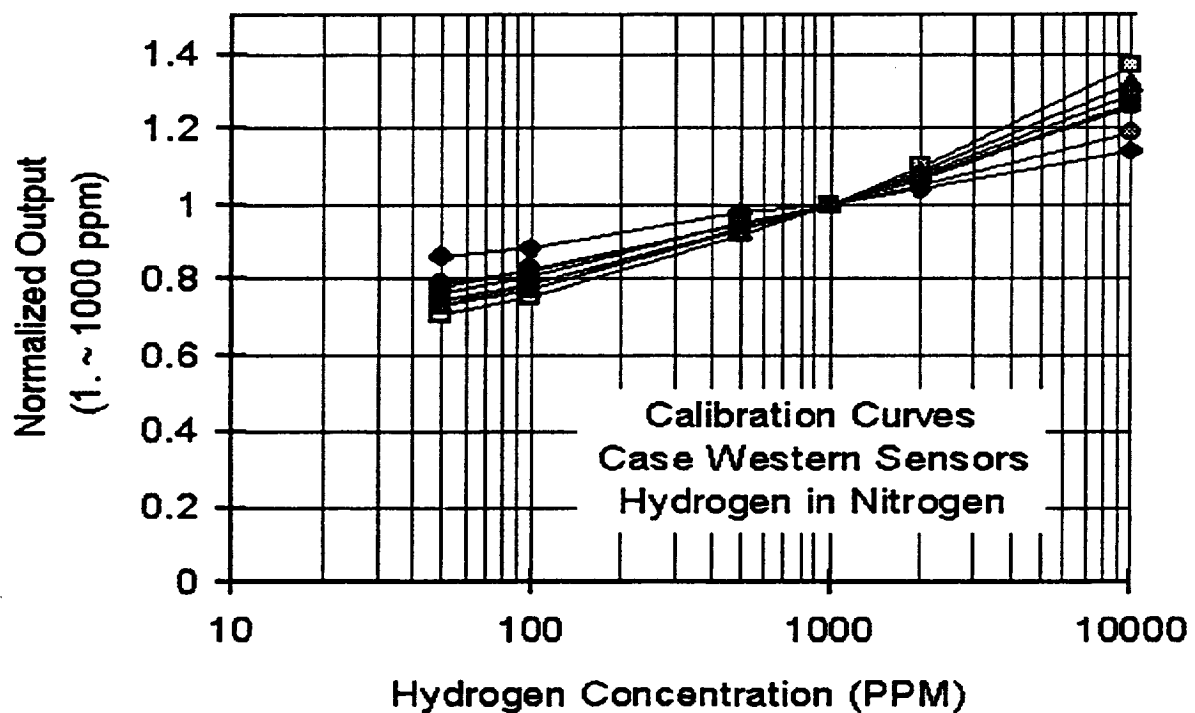


Figure 7. Calibration curves for eight diode sensors. The measured output is normalized so that the response at 1000 ppm hydrogen in nitrogen is set to 1 and all other values are scaled accordingly. The figure shows the similarity in calibration curves for all sensors tested.

Examination of the dynamic responses in Figure 6 indicates the need to use the slope of the sensor response curve if an estimate of leak magnitude is required in less than one second. In previous literature, use has been made of the steady state response value that requires allowing the sensor to stabilize for relatively long periods of time at a fixed condition<sup>3</sup>. This method not only makes calibration time consuming, but it is not relevant to a practical system for which the hydrogen levels may be rapidly time varying. We are studying various algorithms that allow hydrogen mixtures to be characterized by time derivatives or changes in the sensor responses. The difficulty is to find a technique that is simple enough to process in real time yet can be calibrated to the full range of conditions that a single sensor will encounter.

### 3.2 Leak Detection Software and Algorithms

The leak detection software consists of custom filter routines combined with rule-based expert systems and neural networks for fusing information from zone and site hydrogen sensors. The leak system output is a refined list of leak events characterized with prioritize potential leak locations, estimated amounts, and an optional leak plume visualization superimposed on representative view of the fuel system components. The software modules are linked by an "executive system" to facilitate data flow and provide a graphical interface for the user. Heuristic rules based on sensor placement, propellant system configuration, and predominant convection are the basic algorithms for leak source identification and magnitude detection. Two neural network architectures are used in the system to rapidly identify leak locations after only a small number of data cycles for real-time applications. Figure 8 shows a general flow diagram of the response of the detection system to the local atmosphere. The software is required to perform many functions. Some of the key features of the software elements are described below.

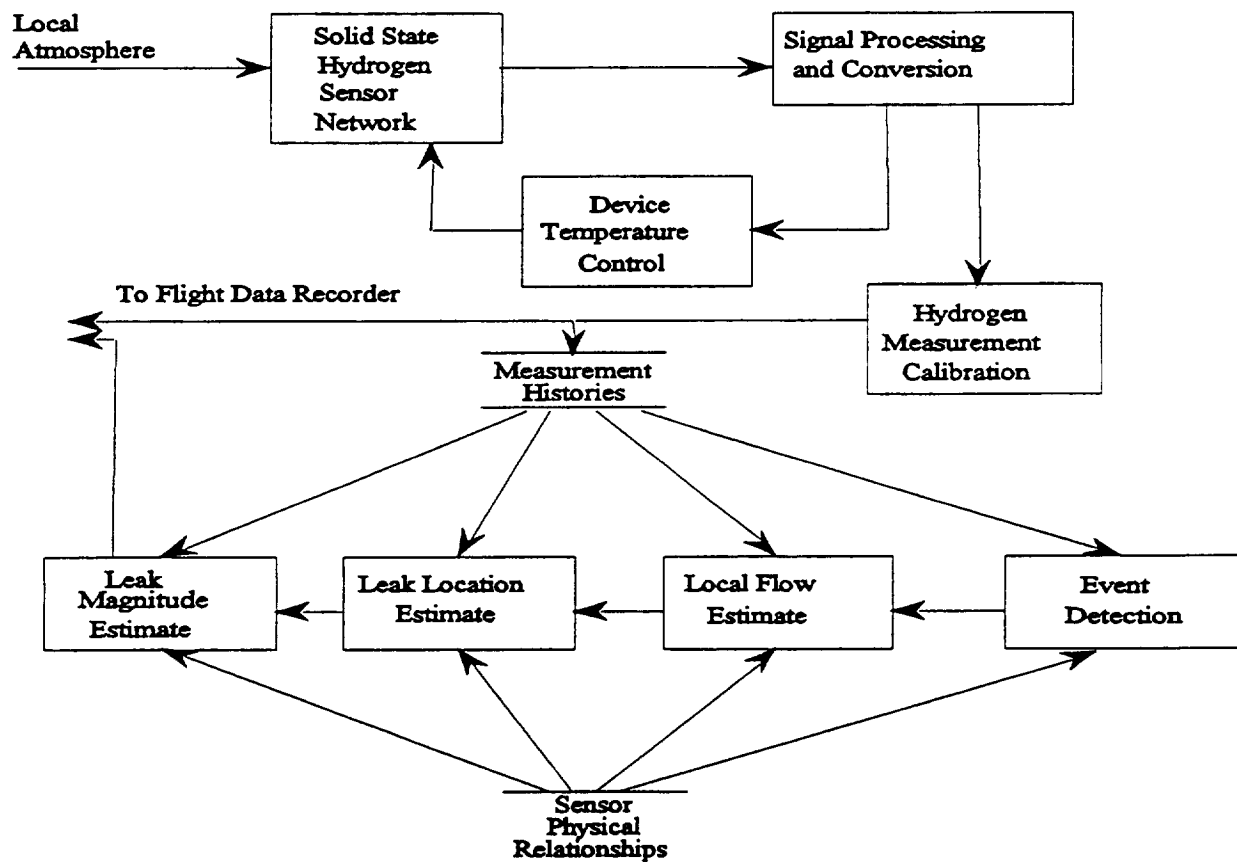


Figure 8. Flow diagram of the response of the detection system to the local atmosphere.

### 3.2.1. Filter Module

The Filter Module is a set of custom routines which scan the recorder data and recognize "significant" events and selects snapshots of the data at these times for analysis by the Expert System and Neural Network modules. The basic algorithm for detecting features involves computing the slope between consecutive data points for all channels. If, for any channel, two slopes in a row are approximately equal, but significantly different from the "expected" slope for the channel, then a significant event is signaled, and the new slope becomes the expected slope.

When a significant event is signaled, a record is created which describes the state of all sensors, including current concentration, whether the concentration is increasing, decreasing, or steady-state, and current rate of change of concentration for the sensors. All event records are transferred to the Expert System Module for analysis.

### 3.2.2. Expert System Module

The Expert System Module uses general heuristics to determine the source of a leak and estimates the direction of any convective current. The module is designed to be quickly adapted to a wide range of physical sensor placements only by describing the network arrangement.

The module computes gas path lengths between sensors and the various gas propagation barriers and transforms the information into a series of "adjacent-to" and "in-between" relationships for the sensors. The "adjacent-to" relations define objects that are "closest" to one another, and the "in-between" relations describes objects that lie spatially between two others. Once the internal system representation is complete, the Expert System Module begins accepting event records from the Filter Module.

The process of detecting and isolating hydrogen leaks involve the following steps.

1. Initialization - The module determines the best time to perform steady-state analysis.
2. Find Regions - The module finds all regions that show evidence of hydrogen.
3. Isolate Sensor Source - For each region, the module finds the sensor closest the leak.
4. Analyze Convection - The module assesses symmetry of detected hydrogen concentrations and determines the leak plume.
5. Isolate Leak Source - The module uses information from steps 3 and 4 to select the best leak source candidate for each region.
6. Estimate Leak Magnitude - The module evaluates hydrogen concentrations versus distance relationships between sensors and the leak source to estimate leak magnitude.

### 3.2.3. Neural Network Module

The Neural Network Module is implemented using NETS software developed at NASA Johnson Space Center. Two neural network architectures are currently implemented in the system and under evaluations. Each take all calibrated sensor concentrations values at two time points as input and output and estimate of the leak location, magnitude, and convective motion of the leak propellant. For the 16 sensor prototype system, the networks use 32 input and 8 outputs, and are trained with one hidden layer of 50 nodes. The first network used data from the first increasing event data set and the first steady-state record afterwards. This network is trained to obtain an estimate of the leak source. The second network used data from the first increasing event data record and the next occurring event regardless of type. The objective of this network is to estimate leaks from initial sensor response data for critical real-time applications.

### 3.2.4. Leak Simulation Module

Sensor data at any given time slice can be displayed as a 3-D image include representations of engine components.

Visualization of leak plume is accomplished using interpolation algorithms to approximate the hydrogen concentration in control volumes between sensors. The measured sensor readings and interpolated values are loaded in Dicer scientific visualization software which performs 3-D display and rotations. The visualization capabilities of the system is designed as a real-time tool for launch personnel to rapidly disseminate the data obtained from the sensor array during prelaunch operations. For flight operations, the visualization tool will be used for post-flight analysis of the data.

#### 4. PROTOTYPE MULTIPLEXING SYSTEM

Aerojet is presently involved with finalizing a design and producing a complete system. Development of a multiplexing system is necessary for actual system operation. To enable a system to operate with a large number of sensors, multiplexing techniques to provide the bias and sensing connections for 16 sensors over 14 lines have been investigated. This technique allows several sensors to effectively share the same cable. The bias voltage is applied through a multiplexer to number of active elements attached to the same line. The simultaneously active elements are differentiated by separate current sensors multiplexed to a common analog to digital (A/D) converter. By scanning the multiplexers, the output of all the sensors on the string can be converted in sequence.

The multiplexer prototype testing has identified some of its limitations. The temperature resistor measurements are implemented as a current measurement to allow multiplexing with the hydrogen sensitive diodes. Although the reverse bias diode currents are insensitive to the applied bias voltage, the temperature resistor currents are quite sensitive to variations in the bias voltage. The voltage drop across the bias multiplexer is dependent on current flow and thus is a source of interchannel interference. The accuracy of the voltage drop compensation limits the number sensors that can be connected to each bias line.

Temperature control is also a limitation of the prototype multiplexer. The hydrogen sensitive devices on each sensor are quite sensitive to the device temperature. Reasonable time responses are available only if the sensor temperatures are held in excess of 50 °C. Even the minimal cooling affects of impinging flows translate to significant variation in the sensor measurements. Active temperature control of each device is an option, however feedback cabling and circuitry would have to be dedicated to each individual sensor. For these sensors, the preferred approach is to provide gross temperature control to all sensors and compensate in the software for the individual measurements for minor variations. A common heater voltage is applied to all devices in parallel. Device to device variation in the heater resistance can be 300% and approximately equal device temperatures can only be achieved by adding device dependent series resistance at the sensor site.

The low level current signals that the sensors provide are susceptible to noise that will limit the length of the multiplexed string of sensors. Adding low pass and notch filters to the conversion circuitry has been considered, however the 200 milliseconds settling time of such filters make adding them after the multiplexer impractical. Filtering can be added to each current detector and this option will be pursued should testing identify excessive noise problems.

Conversion from sensor reading to hydrogen concentrations is processing that will be implemented in the signal processors that digitize, record, and serialize the signals from the sensors. Compensation parameters for the individual sensors and multiplexer effects are individualized to each sensor. Parameter storage and algorithms processing are effected at the local level allowing the ground processor to concentrate on global data fusion.

Aerojet has built a breadboard system multiplexer and network of 16 sensors and is evaluating these techniques in a test facility. In the prototype system, the Data Acquisition function has been implemented using National Instruments LabView software<sup>7</sup> executing on a MAC computer. The LabView software was selected because it supports advanced graphics and easily accommodates programming changes during system evaluation. The Data Acquisition Module performs data sampling from all sensors, does the measurement conversion and displays the results both in numeric displays and on a strip chart recorder. If any values exceed a pre-set threshold, a status light for the sensor is indicated and an audio alarm is sounded. The recorded data is stored to disk by the module. Testing is presently being conducted to verify the operation of the complete system.

#### 5. CONCLUSIONS AND FUTURE PLANS

The combined effort of government, academia, and industry has generated an integrated hydrogen leak monitoring

system. A prototype automated, real-time, hydrogen propellant leak detection system has been developed for launch vehicle applications. The system consists of three elements: (1) a multiplexed sensor array, (2) a signal processing unit, and (3) diagnostic software. The system can monitor low concentrations of hydrogen and visually display the location and magnitude of the leak.

Continued improvement of the system is planned. NASA LeRC and CWRU are attempting to increase the concentration range of the hydrogen sensor to handle a wide range of applications. Processing issues will also be addressed so as to increase the uniformity of the response, heater resistance, and amount of power consumption from sensor to sensor. Later versions the sensor will be micromachined to decrease the sensor power consumption. Aerojet will continue to integrate the NASA LeRC and CWRU sensor into its system hardware with the objective of decreasing the size of the supporting hardware. A flight prototype system is being built for use on the Technology Test Bed Engine at NASA MSFC in 1994.

Although NASA is the largest single user of hydrogen, the use of hydrogen in other applications is wide spread. Thus, the detection of hydrogen in variety of environments is necessary. Commercial applications of this sensor system include in industrial hydrogen production and transportation, and in vehicles which use clean burning fuels. The software can be configured so as to store the magnitude, position, and time of the leak. If desired by the operator, the software can alert remote operators of a dangerous situation and perform appropriate shutdown procedures. For example, an application in which the system described above can be used effectively is leak detection in a pressurized cell. Pressurized mixtures of hydrogen and nitrogen can be placed in the cell and the hydrogen sensors can be placed around the exterior of the cell. The source of the leak can then be visually identified on the screen. This approach has a number of advantages over the traditional helium leak detectors and, at low concentrations of hydrogen, poses at most a small safety concern. Aerojet is aggressively developing this technology for commercial applications which will use not only the NASA LeRC sensors but sensors which detect other gases as well.

## 6. ACKNOWLEDGMENTS

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13. ABSTRACT (Maximum 200 words)  Leaks on the Space Shuttle while on the Launch Pad have generated interest in hydrogen leak monitoring technology. An effective leak monitoring system requires reliable hydrogen sensors, hardware, and software to monitor the sensors. The system should process the sensor outputs and provide real-time leak monitoring information to the operator. This paper discusses the progress in developing such a complete leak monitoring system. Advanced microfabricated hydrogen sensors are being fabricated at Case Western Reserve University (CWRU) and tested at NASA Lewis Research Center (LeRC) and Gencorp Aerojet (Aerojet). Changes in the hydrogen concentrations are detected using a PdAg on silicon Schottky diode structure. Sensor temperature control is achieved with a temperature sensor and heater fabricated onto the sensor chip. Results of the characterization of these sensors are presented. These sensors can detect low concentrations of hydrogen in inert environments with high sensitivity and quick response time. Aerojet is developing the hardware and software for a multipoint leak monitoring system deigned to provide leak source and magnitude information in real time. The monitoring system processes data from the hydrogen sensors and presents the operator with a visual indication of the leak location and magnitude. Work has commenced on integrating the NASA LeRC-CWRU hydrogen sensors with the Aerojet designed monitoring system. Although the leak monitoring system was designed for hydrogen propulsion systems, the possible applications of this monitoring system are wide ranged. Possible commercialization of the system will also be discussed.				
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