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A Small Form Factor Solid-State Hydrogen Sensor Package

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A Small Form Factor Solid-State Hydrogen Sensor Package

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Abstract

The Sandia Robust Hydrogen Sensor is a low power, integrated circuit based miniature hydrogen transducer. This report documents the design, testing, and calibration activities for integrating the Sandia Robust Hydrogen Sensor transducer and supporting electronics into a small form factor package.

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Summary

A hydrogen sensor was required by the Enhanced Surveillance Program (ESP) SN13 task: Embedded Instrumentation for Non-nuclear Components. Based on component gas sample data, a low power sensor capable of measuring hydrogen concentrations from 10 to 10,000 ppm was desired. The Sandia Robust Hydrogen Sensor met the sensitivity and power consumption requirements.

The Sandia Robust Hydrogen Sensor is only a transducer. Considerable supporting electronics are required to bias the hydrogen sensing Field Effect Transistor (FET) on the Sandia Robust Hydrogen Sensor, condition the sensor output, and controllably heat the hydrogen sensing FET to optimize response to changing conditions.

This report documents the design, testing, and calibration activities for producing an integrated transducer and supporting electronics package called the Hydrogen Sensor Board.

Power requirements were quite stringent. Current Integrated Nuclear Materials Management (INuMM) program telemetry packages were using sensors consuming 4 milliamps of current or less. A demonstration model of the INuMM Electronic Sensor Platform, an integrated telemetry/sensor package, had used a Sandia Robust Hydrogen Sensor [Mickelson, 1997]. This implementation of the Sandia Robust Hydrogen Sensor had successfully used only the Field Effect Transistor (FET) portion of the sensor, and, in order to reduce power consumption, had not powered the sensor's FET heaters.

The Hydrogen Sensor Board had several main functions, hydrogen FET power and signal conditioning, power FET (temperature control) power and conditioning and a timing circuit. The board was separated into two sections – hydrogen FET side and power FET side. Each board section required its own power and its own ground. Prior knowledge and circuitry were used whenever available.

The Hydrogen Sensor Board functions were as follows:

Hydrogen FET side of the circuit board

- a. Receive power pulse from the telemetry/data acquisition system.
- b. Generate acceptable voltage and current to power the hydrogen FET.
- c. Scale the hydrogen FET output voltage to match the data acquisition system input requirement.
- d. Provide power FET heater circuit turn on signal at trailing edge of the power pulse from the telemetry/data acquisition system.

Power FET side of the circuit board

- a. Condition Power from an external source.
- b. After receiving a signal from the hydrogen FET side of the board, bring the Sandia Robust Hydrogen Sensor chip up to a prescribed temperature (typically 90°C) for a specific length of time, and then return to room temperature (remove heater power).

Several circuit designs for using the Sandia Robust Hydrogen Sensor were available from past applications. Portions of these designs were used in this design. One circuit in particular is used extensively by Sandia's Microsensor R&D Department for testing and calibrating the Sandia Robust Hydrogen Sensor (version TA770). This design incorporated circuitry to accommodate a wide variation in the hydrogen FET threshold voltages. The hydrogen FET threshold voltage varies noticeably from chip to chip, and wafer to wafer.

The InuMM Electronic Sensor Platform used a circuit designed to use a few milliamps of current as opposed to the Microsensor R&D Department system where current was not a concern. The battery-powered circuit did not include any temperature control circuits because it was an ultra low power system incapable of providing the current levels required by the power FETs. Because, power and circuit area available was limited, this circuit used a voltage doubling circuit to double the 3.6V battery voltage insuring that the hydrogen FET could always be operated at its threshold voltage.

Circuit elements were used from both designs in addition to new elements required by the present application. Several major constraints had impact on the design elements and are listed in Table 1.

Because this circuit required the use of the on-chip heaters the circuit was split into two sections – one for the hydrogen FET side and one for the temperature control side. The hydrogen FET side used the telemetry/data acquisition system battery power while the Power FET side used an external power supply. This posed a potential problem since all the circuitry on the H2 sensor chip shared a common substrate making the substrate a common potential.

The sensor chip also had protection circuits that tied the drain of the hydrogen FET to the drain of one of the power FETs in order to provide ESD protection. The use of a protection circuit diode meant that the FETs drains must be biased properly with respect to each other in order to prevent the diode from being turned on.

Table 1. Design Constraints

Constraint	Design impact	Previous Design inputs
<ul style="list-style-type: none">• Low power draw - <2.5mA – less if possible	Part of the circuit had to use low power parts	
<ul style="list-style-type: none">• Only 3.6 volts available.	Need to generate higher voltage	Single shot doubler circuit was used
<ul style="list-style-type: none">• Single sided power supply	OpAmps must be biased off ground and must operate rail-to-rail.	
<ul style="list-style-type: none">• Temperature control required as an option	Need external power supply for temperature side of circuit Not compatible with need to have low power draw.	Similar to previous design but with max current and timer control added
<ul style="list-style-type: none">• Temperature circuit must turn on (for controlled time) after data acquisition system reads hydrogen FET	A timer must be present in circuit	

One impact of this requirement is that using the hydrogen FET by itself is fine, but using two different power supplies is only good if you don't turn on the protection diode. In this design, voltage is doubled by using a series capacitor technique. This provides very limited current capability. If the protection diode turns on and current is lost to the power side of the circuit, the hydrogen FET is not properly biased and a hydrogen measurement cannot be made.

This means that the hydrogen FET side and the temperature control side must be completely isolated from each other (power and ground). Alternatively, the external power supply (on the power side) must be on at all times to prevent the protection diode from being turned on by the hydrogen FET side of the circuit. It was found through testing that it was impossible to isolate the hydrogen FET and power FET grounds forcing power to be applied to the power terminals at all times even if the power FETs are not operated.

The resulting electronic assembly is shown in Figure 1 and is called the Hydrogen Sensor Board.

Figure 1. The Hydrogen Sensor Board

Two Hydrogen Sensor Boards were constructed and underwent calibration testing from October 1 through November 23, 1998. It was found that hydrogen FETs exposed to varying concentrations of hydrogen and oxygen could have their output voltages described by a single function of the form:

$$\ln\left(\frac{C_{H_2}}{C_{O_2}^{1/3}}\right) = f(V_{out})$$

Figure 2 shows the data and curve fit for hydrogen concentrations ranging from 10 ppm to 10,000 ppm and oxygen concentrations from 3% to 20%.

Figure 2. Polynomial Curve Fit of the Calibration Data

The calibration testing also provided data on how the hydrogen FET works as a sensor device. Some observations are:

1. Some hydrogen FETs show marked shifts in their performance after they have been heated and then cooled. It is recommended that the hydrogen FETs be operated unheated.
2. The speed of response of the hydrogen FETs tested to a step change in hydrogen level is not significantly different between heated and unheated operation when the sensors are in an enclosure with free volume. It is recommended that the hydrogen FETs be operated unheated to reduce power consumption.
3. The hydrogen FETs tested had the same threshold voltage change over a 10 ppm to 10,000 ppm hydrogen concentration range. However, the absolute voltage ranges were quite different. Until hydrogen FETs become much more uniform in their response, each hydrogen FET will have to be calibrated prior to service. A standard calibration curve is not possible.
4. The hydrogen FET output, along with the signal conditioning, is noticeably sensitive to temperature. The hydrogen FET and its signal conditioning must be characterized for temperature response so this may be eliminated during data processing.

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Introduction

A hydrogen sensor was required by the Enhanced Surveillance Program (ESP) SN13 task: Embedded Surveillance for Non-nuclear Components. Based on component gas sample data, a low power sensor capable of measuring hydrogen concentrations from 10 to 10,000 ppm was desired. The Sandia Robust Hydrogen Sensor [Hughes et al, 1994] met the sensitivity and power consumption requirements.

The Sandia Robust Hydrogen Sensor is only a transducer. Considerable supporting electronics are required to bias the hydrogen sensing Field Effect Transistor (FET) on the Sandia Robust Hydrogen Sensor, condition the sensor output, and controllably heat the hydrogen sensing FET to optimize response to changing conditions. Initial specifications for the supporting electronics is shown in Appendix A.

This report documents the design, testing, and calibration activities for producing an integrated transducer and supporting electronics package: the Hydrogen Sensor Board shown in Figure 3.

Figure 3. The Hydrogen Sensor Board.

Theory of Hydrogen FET Operation

In this section, a condensation of Lundström's original paper will be presented to explain the operation of the hydrogen FET [Lundström, 1981].

Figure 4 shows the basic construction and method for operating a hydrogen FET.

Figure 5 shows how hydrogen is adsorbed onto and absorbed into the palladium-nickel layer producing hydrogen ions at the silicon nitride interface. The number of hydrogen atoms at the palladium alloy/silicon nitride interface affects the threshold voltage read out by the circuit in Figure 4.

Specifically, the more atoms present at the palladium alloy/silicon nitride interface, the lower the threshold voltage. The theoretical steady-state drop in threshold voltage due to the presence of hydrogen is related to the concentration of hydrogen in the inert atmosphere above the FET, in terms of gas partial pressure, by the following equation:

$$\frac{1}{\Delta V} = K_1 \sqrt{\frac{1}{P_{H_2}}}$$

Figure 4. Construction and operation of a Hydrogen-Sensitive FET

Figure 5. Pictorial representation of hydrogen interacting with the palladium alloy/silicon nitride junction.

When oxygen is present, the hydrogen and oxygen atoms interact at the surface of the palladium alloy producing water and reducing the number of hydrogen atoms present at the palladium alloy/silicon nitride interface, thereby reducing the threshold voltage drop. The equation for the theoretical steady-state drop in threshold voltage becomes:

$$\frac{1}{\Delta V} = K_2 \sqrt{\frac{P_{O_2}}{P_{H_2}}}$$

where now the partial pressure of oxygen plays a role in defining the drop in threshold voltage.

In his paper, Lundström notes that theory does not fully represent all of the complexities of reality. In the chapter discussing the calibration data, we will see how well theory matches observed behavior.

Electronic Design and Fabrication

Sandia Robust Hydrogen Sensor

The Sandia Robust Hydrogen Sensor is wide range hydrogen sensor using a Field Effect Transistor (FET) with a catalytic metal gate for measuring hydrogen concentrations below 10,000 ppm and a catalytic metal chemiresistor for measuring hydrogen concentrations above 10,000 ppm to 95%.

The hydrogen FET chip was available in several versions. One version (typically used in development) contained a number of hydrogen FETs, A hydrogen sensing chemiresistor, multiple bipolar junctions used for temperature monitors and several power FETs used for chip heating. An image of the chip is shown in Figure 6. Figures 7 and 8 show the active FET.

When packaged as a 16 DIP package, the Sandia Robust Hydrogen Sensor appears as shown in Figure 9. The wiring description for the 16 pin DIP package, called the TA770, is shown in Figure 10.

Figure 6. Layout of the Sandia Robust Hydrogen Sensor.

Figure 7. Closeup view of Sandia Robust Hydrogen Sensor. The serpentine trace at the top of the picture is the chemiresistor. The circled Field Effect Transistor is the active FET on this device. The other FETs visible are spares. The dark splotches are dust particles.

Figure 8. Closeup view of the active FET.

Figure 9. The Sandia Robust Hydrogen Sensor packaged as a 16 pin Dual Inline Package.

Figure 10. Pin Designations for the TA770 (16 pin DIP) Sandia Robust Hydrogen Sensor.

Circuit Design

The Hydrogen Sensor Board had several main functions: hydrogen FET power and signal conditioning, power FET (temperature control) power and conditioning and a timing circuit. The board was separated into two sections – hydrogen FET side and power FET side. Each board section required its own power and its own ground. Prior knowledge and circuitry were used whenever available.

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- d. Provide power FET heater circuit turn on signal at trailing edge of the power pulse from the telemetry/data acquisition system.

Power FET side of the circuit board

- a. Condition Power from an external source.
- b. After receiving a signal from the hydrogen FET side of the board, bring the Sandia Robust Hydrogen Sensor chip up to a prescribed temperature (typically 90°C) for a specific length of time, and then return to room temperature (remove heater power).

Several circuit designs for using the Sandia Robust Hydrogen Sensor were available from past applications. Portions of these designs were used in this design. One circuit in particular is used extensively by Sandia's Microsensor R&D Department for testing and calibrating the Sandia Robust Hydrogen Sensor (version TA770). This design incorporated circuitry to accommodate a wide variation in the hydrogen FET threshold voltages. The hydrogen FET threshold voltage varies from chip to chip, and wafer to wafer.

A previous project in the Integrated Nuclear Material Management (INuMM) program had designed a circuit for use with their battery powered measurement system. Their circuit was designed to use a few milliamps of current as opposed to the Microsensor R&D Department system where current was not a concern. The battery-powered circuit did not include any temperature control circuits because it was an ultra low power system incapable of providing the current levels required by the power FETs. Because, power and circuit area were limited, this circuit used a voltage doubling circuit to double the 3.6V battery voltage insuring that the hydrogen FET could always be operated at its threshold voltage.

Circuit elements were used from both designs in addition to new elements required by the present application. Several major constraints had impact on the design elements and are listed in Table 2.

Because this circuit required the use of the on-chip heaters the circuit was split into two sections – one for the hydrogen FET side and one for the temperature control side. The hydrogen FET side used the telemetry/data acquisition system battery power while the Power FET side used an external power supply. This posed a potential problem since all the circuitry on the H2 sensor chip shared a common substrate making the substrate a common potential.

One impact of this requirement is that using the hydrogen FET by itself is fine, but using two different power supplies is only good if you don't turn on the protection diode. In this design, voltage is doubled by using a series capacitor technique. This provides very limited current capability. If the protection diode turns on and current is lost to the power side of the circuit, the hydrogen FET will not be properly biased and a hydrogen measurement cannot be made.

Table 2. Design Constraints

Constraint	Design impact	Previous Design inputs
<ul style="list-style-type: none"> • Low power draw - <2.5mA – less if possible • Only 3.6 volts available. 	Part of the circuit had to use low power parts Need to generate higher voltage	Single shot doubler circuit was used
<ul style="list-style-type: none"> • Single sided power supply 	OpAmps must be biased off ground and must operate rail-to-rail.	
<ul style="list-style-type: none"> • Temperature control required as an option 	Need external power supply for temperature side of circuit Not compatible with need to have low power draw.	Similar to previous design but with max current & timer control added
<ul style="list-style-type: none"> • Temperature circuit must turn on (for controlled time) after data acquisition system reads hydrogen FET 	A timer must be present in circuit	

This means that the hydrogen FET side and the temperature control side must be completely isolated from each other (power and ground). Alternatively, the external power supply (on the power side) must be on at all times to prevent the protection diode from being turned on by the hydrogen FET side of the circuit. It was found through testing that it was impossible to isolate the hydrogen FET and power FET grounds forcing power to be applied to the power terminals at all times even if the power FETs are not operated.

Figure 11 presents the complete Hydrogen Sensor circuit design. This circuit can be broken down into four key sub-circuits:

1. A constant current source for biasing the FET.
2. A zero and scale adjustment.
3. Voltage doubling for operation from a 3.6V battery.
4. Triggered heater control.

These sub-circuits will each be discussed separately in detail in subsequent sections.

A parts list for the Hydrogen Sensor Board is presented in Table 3.

Figure 11. Electrical Schematic for the Hydrogen Sensor Board

Table 3. Parts List for the Hydrogen Sensor Board

Part Designation	Part Description	Part number	Supplier
U1 and U2	MAX407 or LT1112 or LT2178	MAX407ESA	Maxim or Linear Technology
U3	MAX407 opamp	MAX407ESA	Maxim
U4	ICM7240UE (IPE can be used) timer	ICM7240UE	Maxim
U5	MAX407 opamp	MAX407ESA	Maxim
U6 and U7	LT1634 4 volt reference	LT1634AIS8-4.096	Linear Technology
U8	LM134H-3 current source - set to approx 100μA	LM134H-3	National
U9	IMX2 bipolar transistors	IMX2	Rohm
U10	MOC223 opto isolator		Motorola
U11	IRF7105 power MOSFET	IRF7105	International Rectifier Corp
U12	Sandia Robust Hydrogen Sensor – TA770	TA770-001	Sandia National Labs
	ALL RESISTORS ARE SIZE 0805 UNLESS SPECIFIED	Resistors are 10% 200ppm unless specified	Any manufacture is acceptable if they meet the specs
R1	Select for desired diode current – approx 4.7k		Any
R2 and R3	47k	1% 25ppm	Any
R4	short		Any
R5	Open		Any
R6	10k - not critical – used as pullup		Any
R7	10k	1% 25ppm	Any
R8	220k	1% 25ppm	Any
R9	100k pot – not critical – trade off against current reqmts	Bourns 3262	Vishay(preferred) or Bourns
R10	short		Any
R11	10k		Any
R12	100k pot		Vishay(preferred) or Bourns
R13	1k – not critical		Any
R14	2.2ohms – size 1206 – current sense resistor – 5%	P2.2BCT	Panasonic
R15	2.2ohms – size 1206 – current sense resistor – 5%	P2.2BCT	Panasonic
R16, R17, and R18	4.7k		Any
R19	220k timer charge resistor	1% 100ppm	Any
R20	10k		Any
R21	100k		Any
R22	1M pot (high quality – stake after setting)	Bourns 3262	Vishay(preferred) or Bourns
R23	Not used – open		Any
R24	15k	1% 25ppm	Any
R25	1.5k	1% 25ppm	Any
R26	100k	1% 25ppm	Any
R27	Short		Any
R28 and R29	560k	1% 25ppm	Any
R30	1M pot (high quality – stake after setting)	Bourns 3262	Vishay(preferred) or Bourns
R31	Short		Any
R32	87k		Any
R33	1M pot (high quality – stake after setting)	Bourns 3262	Vishay(preferred) or Bourns
R34	Not used		
R35	2.7k		Any
R36	1M – not critical		Any
R37	1M – not critical		Any
R38	1k – 10k		Any
R39	560 ohms		Any

Table 3. Parts List for the Hydrogen Sensor Board - Continued

Part Designation	Part Description	Part number	Supplier
D1	Not used – use a jumper		
D2	Not used – use a jumper		
D3	1N457		Any
	ALL CAPACITORS ARE SIZE 1206 UNLESS SPECIFIED		
C1	10 μ F – not critical – EIA size C		Any
C2	Not used – open – use to control response or oscillation		Any
C3	10 μ F – controls timing – EIA size C		Any
C4	.1 μ F – not critical –		Any
C5	68 μ F – controls current available during doubling-size C		Any
S1	External switch		Any

Current Source

The current source used on the board is a LM134 which is set to approximately 100 μ A. The circuit for the current source is shown in Figure 12. Diode D3 and resistors R24, R25 form a temperature compensation network for the LM134. The selection of R24 and R25 is based on calculations from the LM134 data sheet and allow the V_{tc} of the diode to create a current which compensates for the change in the LM134 current over temperature (provided R24 and R25 are correctly selected).

There are several problems with this circuit. If you need to adjust the current (which you might want to do to adjust the temperature coefficient of the hydrogen FET) then you need to change one of the compensation resistors but, if you do that, then the temperature compensation is no longer valid. Table 4 shows how the temperature coefficient of the current source varies with a change in R24.

Figure 12. Constant Current Source Circuit.

Table 4. Effect of R24 Resistance on the Current Source Temperature Coefficient

R25 (k ohms)	I current source (μ A)	temperature coefficient (μ A/C)
1.5	89.6	-.0002
1.4	92.87	.0106
1.3	96.59	.0231
1.2	100.1	.0376
1.1	106	.0548
.9	119.7	.1
.8	129.	.1322

Note that for optimal compensation, the ratio of R24 to R25 is 10:1. When you drift away from that ratio, the temperature coefficient of the current source gets worse. For small shifts away from the ideal ratio the temperature coefficient remains reasonable but for larger changes in the ratio (.8k R25 vs. 15k R24) the temperature coefficient is objectionable and would create problems if the environment temperature varied more than 10 degrees from nominal. In practice, we did not adjust the current so the circuit values could remain at the correct ratio. However, if the current needs to be adjusted then you would need to reselect values for the two resistors before using the circuit.

A second problem with this current source is that if fast temperature changes are anticipated then the diode and LM134 will change temperature at different rates causing a large transient effect. Because of the way our system was to be used (inside a second larger system) fast temperature changes were unlikely, and hence, the LM134 was a workable solution. One cure for this problem is to use a diode (or transistor junction) which is thermally tied to the LM134. This is a typical approach and it is surprising that the LM134 does not include an internal diode for this purpose. Experimental data shows that this solution can greatly reduce transient effects compared to using the two devices mounted to a circuit board [Jenkins and Anderson, 1999].

An alternate board was designed to address the above problem and uses a current source which utilizes a opamp to regulate the current through the hydrogen FET rather than use the LM134 current source. The version 2 circuit will be discussed in Appendix B.

Several other factors need to be mentioned in this section. One problem with the hydrogen FETs that were used in this project is that they have a threshold voltage of around 3V (at 25°C 0 ppm H₂). This means that a minimum voltage needed to run this

circuit is the threshold voltage plus the voltage required by the current source. For the standard circuit, this is about:

$$3V \text{ (threshold voltage)} + 0.9V \text{ (LM134 current source)} + 0.6V \text{ (diode)} = 4.5 \text{ volts.}$$

If you use the alternate circuit then the minimum is:

$$3V \text{ (threshold voltage)} + 0.5V \text{ (current sense)} = 3.5 \text{ volts.}$$

Either way, the required voltage is too high to be run from a battery system limited to 3.6 volts. This is why the circuit contains a voltage doubler. Fortunately, the threshold voltage decreases with increasing hydrogen concentration. A solution for the normal, zero hydrogen condition remains a solution throughout the sensors operating range.

Some hydrogen FETs have been produced with threshold voltages near 2.6 volts, but these were unavailable for this sensor board development.

Gain Block and Level Adjustment

The hydrogen FET output signal conditioning consists primarily of low power opamps used to amplify the hydrogen FET threshold voltage and level shift the signal into the proper range for use by the data acquisition system. The input required by the data acquisition system is 0.4 to 1.4 volts. The output from a typical hydrogen FET is from 3 to 2.6 volts over the range of interest. The average gain is 2.5 and includes a 1:1 signal inversion. Figure 13 shows the circuit used to accomplish these requirements.

Figure 13. Zero and Scale adjusting circuit

A current produced by the previously discussed current source (U8) feeds the hydrogen FET whose drain is shorted to its gate. This configuration causes the hydrogen FET to bias at its threshold voltage for that specific current. This current must be selected to be near the zero temperature coefficient point for the FET or the threshold voltage will change significantly with temperature.

Since the hydrogen FET is very sensitive to a change in its drive current, a buffer is used to isolate the hydrogen FET current from the processing circuits. U3a is configured as a high impedance buffer, and prevents any loss or change of current through the hydrogen FET due to loading. The output from U3a is the hydrogen FET threshold voltage and needs to be scaled, shifted and inverted.

The second stage (U3b) accomplishes all of the 3 goals, it 1) provides an initial level shift, 2) provides gain and 3) provides signal inversion. The output stage (U5b) is configured as a non-inverting level shifter.

A voltage reference is provided in order to accurately set the references for the level shifting operations. The LT1634 was selected because it is a good compromise between accuracy and current consumption. Since the signal conditioning side of the Hydrogen Sensor Board was to run on a current under 2.5mA the components need to be low current versions. The LT1634 is not as good as a higher current source, but it only draws 40 μ A plus use current. The LT1634 is set up for about 40 μ A with about 4 μ A being drawn for each of the level shift pots. The reference level for the output shifter is buffered by U5a in order that the set-point at the R33 wiper is not changed when R33 is changed. This is not necessarily required, but without it, the reference would change and make adjustment somewhat more difficult. This needs to be traded off against the cost of the current used by the buffer but in this case the opamps are duals and very low current.

Setting the shift levels and gain requires several iterations and the process is reviewed in the next few paragraphs. The objective is to map the output from the hydrogen FET to the input range required by the data acquisition system. Since each hydrogen FET can be different we will review as an example a hydrogen FET which has a response to hydrogen concentration of 3.0V to 2.6V. This voltage variation needs to be mapped to the 0.4 to 1.4 volts required by the data acquisition system. This gives a gain of 2.5 with an inversion. Table 5 below shows the input and output from each of the signal processing stages with the indicated reference values and a U3b gain of 1.25.

Table 5. Voltages through the gain block and level shifters

Threshold Voltage, Vth (U3a +input)	U3b output (gain+shift) Ref = 2.15v	U5b output (final output) Ref = 1.75v
3.00v	1.08v	.41v
2.90	1.21	.66
2.80	1.33	.91
2.70	1.45	1.16
2.6	1.58	1.41

In practice, the first reference (the ref into U3b +) is set to a level which will guarantee that over the input range from the hydrogen FET buffer the output from U3b will not get too close to either rail. The gain is then adjusted to yield the required output range, followed by an adjustment of the U5b reference (U5a output) which moves the overall curve to the 0.4V starting point.

In general it takes several iterations to get the gain set to the proper level. A variable resistor was substituted for the hydrogen FET to do this adjustment. This resistor was adjusted to simulate whatever range a particular hydrogen FET exhibited. This could also be accomplished using a power supply at the input but the resistor produces the same conditions as the hydrogen FET and it can be handily substituted when needed.

Since the circuit is intended to function with a single ended supply, all the opamps must be biased off ground. This means that you need to use opamps which handle near rail to rail inputs and outputs.

Voltage Doubling

In order to operate off of a lithium battery supplying 3.6 volts while being able to bias the hydrogen FET to a threshold voltage of as much as 4 volts (plus the current source voltage drop) required a circuit to increase the supplied battery voltage. Rather than use a DC to DC power converter which would consume too much power, a voltage doubling circuit using two switching FETs (U11) and a capacitor (C5) to temporarily increase the voltage supplied to the constant current source and the zero and scaling circuit to about 7.2 volts.

Figure 14 shows the voltage doubling circuit. The capacitor was charged to 3.6V during the period between the polling of the Hydrogen Sensor Board by the telemetry system. Charging is accomplished through R37 from a constant 3.6 volts applied by the

Also shown in the figure are 3 components that are actually part of the timer circuitry discussed in the next section. These components (U10, R34 and R35) form an opto isolator circuit used to trigger the heater timer which provide total isolation of the heater / timer from the measurement circuits. The isolator current is taken from the 3.6 volt side of the circuit in order not to draw any current from the doubling capacitor. The isolator draws about 1.5mA whenever the 3.6V FET Power is high.

Figure 14. Voltage Doubling Circuit.

FET Heater Control

The Hydrogen Sensor Board included a versatile heater control circuit. The Sandia Robust Hydrogen Sensor includes as part of the integrated circuit two power FETs and a diode (D5) used as a temperature sensor. The power FETs are driven to heat the Sandia Robust Hydrogen Sensor to 90°C with feedback control provided by the diode.

In a typical application, heating the Sandia Robust Hydrogen Sensor gives more rapid response to changing hydrogen levels. It was originally believed that it might be necessary to heat the Sandia Robust Hydrogen Sensor intermittently in order to have it correctly measure even a slowly changing hydrogen level. During calibration testing, it was found that the heaters were unnecessary for the anticipated application that would track slowly changing hydrogen levels over several months.

The heater circuit monitors (via U10 opto-isolator shown in Figure 11 and 14) the “3.6v FET Power” line from the telemetry system. When the heater circuit senses the power line falling from 3.6 volts to 0 volts, it switches on the heaters for a period of time selected by jumpering the correct inputs of the timer chip (U4). The heaters can be manually switched on by closing switch S1. The peak current drawn by the heaters can be limited by adjusting R12. The heaters are powered by external power source set at 7.2 volts.

The heater control circuit (Figure 15) consists of 5 parts:

1. a voltage reference (U9),
2. a temperature monitor (U1a, D5),
3. a control block (U1b, U2a),
4. a current limiter (U2b), and
5. a timer (U4, U9, U10, U13).

A voltage reference is needed for a number of functions. It is used to set the temperature reference point and to set the temperature diode current.

The temperature monitor consists of a diode on the hydrogen FET die and opamp U1a and it's associated resistors. The hydrogen FET die has 9 diodes available for temperature measurement and selection depends on what point on the die will be used to set the temperature. For this application diode D5 is used to monitor temperature.

The current through the monitor diode must be constant in order to provide a good measurement of temperature, otherwise V_{be} would be a function of both temperature and current. The current control opamp uses a reference on its + input to fix the voltage across R1 which in turn fixes the current through the diode. The current used is about 10 μ A but is adjustable either by the resistive divider or by changing the value of R1.

Figure 15. Heater Control Circuit.

The next part of the circuit is the control block. The section consists of U1b and U2a and associated components. U2a is a buffer that accepts the temperature setpoint from R9 and passes it to the control amp U1b. The buffer is not strictly necessary, but it allows the current input to the control amp to be independent of the setpoint resistor. The control amp amplifies the difference between the temperature monitor and the temperature reference, and provides an output used to drive the heater FETs. Components R7, R8, R10, and C2 control the gain and response of the system.

The output of the control block is run through a voltage to current controller which can be used to set the maximum current which will flow through the power FETs. The circuit insures that for any given supply voltage you can limit the max power dissipated by the FETs. The peak FET current can be adjusted by R12. Opamp U2b is configured as the current controller. Whatever voltage is on the wiper of R12 will appear across the parallel combination of R14/R15 due to the action of the opamp driving the FET gates to a level producing the voltage match.

The last part of the heater control section is the timer. The timer consists of U4, U13, U9, U10 and the associated resistors and capacitors. As discussed previously U10 is an opto isolator that provides the trigger input for the timer. Whenever there is voltage

applied to the 3.6V FET power input (measurement side of circuit) U10 shorts the R20, C4 node to ground. This causes C4 to discharge. When the 3.6v FET power input returns to ground (the measurement side turns off) C4 will recharge producing a positive spike on timer pin 11, which sets the timer latch, initializing the timer period. U13 is a MAX63xx (a number of trigger voltages/devices can be used) reset chip used only to guarantee that the timer is in the off state on power up.

The heart of the timer is the ICM7240 (U4) timer chip. The timer chip consists of a 555 type timer and an integrated long chain divider. The basic timing period is set by R19 and C3 and is simply the RC time. In this application R19 is 220k ohms and C3 is 10 μ F giving a period of 2.2 seconds. Timer pins 1-8 are used to select which divider output is used as the final output. This allows a multiplier of 1 to 128 to be applied to fundamental timing period for a final timer output of 2.2 to 282 seconds. For this application a multiplier of 128 is selected to give a timer period of about 5min. When the timer is in the off state the voltage on R12 is clamped (by transistor 2 in U9) to ground preventing the heater from operating. When the timer is triggered, this voltage is released (U9 transistor 2 off), and the heater will power up and reach a regulation state. A switch port (S1) is provided which can be used to enable the heater for setup purposes.

Board Layout and Interfaces

The Hydrogen Sensor Board was implemented on a two-layer circuit board with parts mounted on one side only. The general arrangement is shown in Figure 16.

The Hydrogen Sensor Board may be operated from the telemetry system battery or from external power. Figures 17 and 18 show how connections are to be made according to the operating mode.

Note that external power must be applied even when operating the Hydrogen Sensor Board from the telemetry system battery power. This is because ground loops were discovered passing through the Sandia Robust Hydrogen Sensor substrate and the heater circuitry. By biasing the external power connection with 7.2 volts, the oscillations were defeated. If battery operation is desired, the heater circuit should be eliminated altogether which will then eliminate the ground loop.

Figure 16. Hydrogen Sensor Board Layout

Figure 17. Connections for Powering the Hydrogen Sensor Board from an External Power Supply.

Figure 18. Connections for Powering the Hydrogen Sensor Board from the Battery Powered Telemetry System. External power must be applied to prevent oscillations in the output signal.

Calibration

The calibration of the Hydrogen Add-On boards was conducted using a set of precision metering valves, nitrogen, oxygen, and hydrogen gas supplies, a sealed chamber, the add-on boards, and computer controlled voltmeters to read the add-on board output signal. Figure 19 illustrates the system.

Calibration Data

The add-on hydrogen board calibration series started on October 1, 1998 and ended on November 23, 1998. Table 6 lists the data files taken during the calibration tests.

Calibrations performed from October 1, 1999 to October 28, 1998 were to establish the operating characteristics of the boards and FETs. Several FETs were tried in board 1 until satisfactory results were achieved.

Once the FETs were selected and characterized, the signal conditioning zero and span were reset for the purposes of a test application. The calibration run on October 30, 1998 is the key calibration data.

After the October 30, 1998 calibration test, 3 calibration tests were performed where an INuMM ESP miniature data acquisition/telemetry system powered the FET circuit with the battery internal to the INuMM ESP.

Figure 19. Calibration System

Table 6. Calibration Data Files

Test Title	Board 1 FET	Board 2 FET	Heated	Notes
GTB1_100198.001	2391	2541*	Y	
GTB1_100298.001	2391	2541*		
GTB1_100798.001	2391	2541*	Y	
GTB1_101298.001	2542	2541*	Y	
GTB1_101398.001	2386	2541*		
GTB1_101498.001	2542	2541*	Y	
GTB1_101598.001	2542	2541*		
GTB1_101698.001	2536	2541*	Y	
GTB1_101698.002	2536	2541*	Y	
GTB1_101898.001	2536	2541*		44 hour test
GTB1_102198.001	2536	2541*		
GTB1_102298.001	2536*	2541		
GTB1_102398.001	2536*	2541		
GTB1_102698.001	2536*	2541		
GTB1_102898.001	2536*	2541	Y	
GTB1_103098.001	2536*	2541		
puck4c_2.xls	2536*	2541		
puck1116.xls	2536*	2541		
puck1123.xls	2536*	2541		

*Indicates the FET which was directly in front of the incoming gas flow

Note: all heated FETs were heated to 90°C

Note: in the tests whose title begins with 'puck', the Hydrogen Sensor Board was powered via the battery in the telemetry package and used the voltage doubling circuitry on the Hydrogen Sensor Board. All other tests used a laboratory power supply to power the Hydrogen Sensor Board and bypassed the voltage doubling circuitry.

Figure 20. Typical Output Data for Hydrogen Sensor Board Calibration.

FET Response to a Hydrogen/Nitrogen Atmosphere

As discussed in the theory section, the response of the hydrogen FETs tested in a non-oxygen containing atmosphere should follow the equation:

$$\frac{1}{\Delta V} = K_1 \sqrt{\frac{1}{P_{H_2}}}$$

Since we wish to determine the concentration of hydrogen, this equation is rearranged to:

$$\sqrt{C_{H_2} P_{amb}} = K_3 V_{out}$$

where now the partial pressure of hydrogen is expressed as the product of the hydrogen concentration and the ambient pressure. Note also that the output voltage from the hydrogen sensor board replaces the change in threshold voltage since the board output voltage is linearly related to the threshold voltage.

Figure 21 shows the data for FET 2541 at hydrogen concentrations ranging from 9.5 to 10,000 ppm taken on October 30, 1998. The data shows marked non-linearities and does not follow theory. In fact, the curve fit shown requires that the concentration ratio data be transformed by a log function and then curve fitted to the voltage data by a 3rd order polynomial. FET 2536 shows similar behavior.

Figure 21. Response of Hydrogen FET 2541 to varying hydrogen concentrations in a nitrogen atmosphere.

Effect of Oxygen on FET Response to Hydrogen

When oxygen is present, the response of the FET by theory should follow the form of the equation:

$$\frac{1}{\Delta V} = K_2 \sqrt{\frac{p_{O_2}}{p_{H_2}}}$$

Rearranging this equation similarly to the previous section, the hydrogen sensor board output can be related to the square root of the ratio of the hydrogen and oxygen concentration:

$$\sqrt{\frac{C_{H_2}}{C_{O_2}}} = K_4 V_{out}$$

Figure 22 shows the data for hydrogen concentrations from 9.5 to 500 ppm in a nitrogen atmosphere also containing 3%, 5% and 20% oxygen. The data was taken on October 30, 1998. In this case, the data does show that at low hydrogen concentration, the response tends to follow theory and fitting a straight line.

However, when the data is extended over the entire range of hydrogen concentrations, see Figure 23, the response does not follow theory and is nonlinear. As it was in the case of no oxygen present, the response is logarithmic.

Figure 22. Response of Hydrogen FET 2541 to low hydrogen concentrations in a nitrogen/oxygen atmosphere

Figure 23. Response of Hydrogen FET 2541 for hydrogen in a nitrogen/oxygen atmosphere.

Curve Fits

It can be seen that the square root of the concentration ratio can be a useful means for accounting for the combined effect of hydrogen and oxygen on the FET response. Yet, the data has scatter above a sqrt(concentration ratio) of 0.1.

After some trial and error with curve fits, it was found that a better relationship for describing the data was:

$$\ln\left(\frac{C_{H_2}}{C_{O_2}^{1/3}}\right) = f(V_{out})$$

A plot of the data using this new ratio for FET 2541 is shown in Figure 24. The data for each oxygen concentration is shown as a different symbol. The data is more tightly clustered. Figure 25 shows the same data plotted with a logarithmic y axis. The data shows a distinct S curve that is typical of all of the data taken during calibration. A straight-line fit does a moderately good job of fitting the data, but the best fit is achieved using a 5th order polynomial. See Figure 26.

Figure 24. Response of Hydrogen FET 2541 to hydrogen concentrations in a nitrogen/oxygen atmosphere replotted using a new concentration ratio.

Figure 25. Figure 24 plotted with a logarithmic y axis.

Straight Line Fit, R=0.9525

Polynomial Fit, R=0.9905

Figure 26. Comparison of a straight-line and 5th order polynomial fit.

The general form of the curve fits for the FET response data will take the following forms:

$$\ln\left(\frac{C_{H_2}}{C_{O_2}^{1/3}}\right) = a_0 + a_1 V + a_2 V^2 + a_3 V^3 + a_4 V^4 + a_5 V^5 \quad 3\% \leq C_{O_2} \leq 20\%$$

$$\ln\left(\sqrt{C_{H_2} \cdot p_{amb}}\right) = a_0 + a_1 V + a_2 V^2 + a_3 V^3 \quad C_{O_2} = 0\%$$

where

C_{H_2} = hydrogen concentration

C_{O_2} = oxygen concentration

V = output voltage from hydrogen sensor board.

p_{amb} = absolute ambient pressure, torr

The coefficients for the equation for FETs 2536 and 2541 are shown in Table 7.

Table 7. Curve Fit Coefficients for FETs 2536 and 2541

	FET2536	FET2536	FET2541	FET2541
	0% O ₂	3% to 20% O ₂	0% O ₂	3% to 20% O ₂
a ₀	555.920303	-831.7510205	1980.628762	-6700.067801
a ₁	-1452.466276	4549.54556	-4619.140477	30617.21838
a ₂	1243.926974	-10052.46009	3565.768277	-56001.10913
a ₃	-349.6783791	11050.6961	-911.4436491	51132.75959
a ₄	0	-6024.157619	0	-23288.86811
a ₁	0	1301.58943	0	4231.305477
R	0.9990	0.9910	0.9990	0.9905

Performance

Repeatability and Accuracy

Each time that the FETs were heated, the unheated reading shifted. Tables 8 and 9 illustrate what was observed. The sequence of calibration runs occurred as listed below:

October 15, 1998	FET heaters off
October 16, 1998	FET heaters on
October 18, 1998	FET heaters off
October 21, 1998	FET heaters off

When a heated calibration occurred between 2 unheated calibrations, the FETs showed a shift in their response. Table 8 shows that FET 2536 had a .4% to 5% shift and FET 2541 had a noticeable shift at sub 1000 ppm levels, but not much effect above 1000 ppm. Table 9 shows the results when 2 calibration runs at room temperature (heaters off) were performed consecutively without an intervening heated calibration. Both FETs show a variation of only 1% to 2% over most of the calibration range.

Heating may have a stabilizing effect on FET performance variation. FET 2541 had been cycled from 90 C to room temperature several times in earlier testing, but FET 2536 was first heated on October 16. This indicates that it is possible that the FETs vary upon heating and cooling initially and eventually 'break-in' after enough temperature cycles and are no longer affected by temperature cycles. Unfortunately, we did not have the time to continue cycling the FETs to determine their long-term behavior. Lacking better information, it seems that maintaining the FETs at a constant temperature will result in more consistent, repeatable measurements.

A high temperature anneal at 250 C in a 2% hydrogen/98% nitrogen atmosphere results in more consistent FET behavior [Hughes, 1998]. We had initially planned to use annealed FETs, but the first batch of FETs that were annealed had a very high failure rate. Therefore, rather than destroy most of our stock of FETs in the annealing process, we used un-annealed FETs in the Add-On boards. It is possible that the temperature cycling during calibration may be having a similar, though slower and less destructive, effect as the annealing process.

Lastly, if a constant operating temperature is desired, it is difficult to calibrate at 90 C, and then install the FET into an instrumentation package, which is then installed into a test device, without turning power off to the FET, and having it return to room temperature. Therefore, it seems that a room temperature calibration and application of the FETs is preferred for consistent, repeatable measurements.

Table 8. Comparison of unheated calibration results when the FETs were heated in between.

2536 at 0% O2 - Unheated					2541 at 0% O2 - Unheated				
	15-Oct	18-Oct	Delta	% Change		15-Oct	18-Oct	Delta	% Change
9.5	1.0117	1.1930	0.1814	17.93	9.5	0.9808	1.2643	0.2835	28.90
50	1.2008	1.2461	0.0453	3.77	50	1.3024	1.3194	0.0170	1.30
100	1.2244	1.2647	0.0403	3.29	100	1.3327	1.3380	0.0053	0.40
500	1.2574	1.3012	0.0438	3.48	500	1.3652	1.3750	0.0098	0.72
1000	1.2716	1.3176	0.0460	3.62	1000	1.3856	1.3915	0.0058	0.42
2000	1.2848	1.3336	0.0489	3.80	2000	1.4025	1.4075	0.0050	0.35
5000	1.3016	1.3544	0.0528	4.06	5000	1.4205	1.4282	0.0077	0.54
8000	1.3105	1.3657	0.0552	4.21	8000	1.4289	1.4395	0.0105	0.74
10000	1.3142	1.3701	0.0559	4.25	10000	1.4332	1.4440	0.0109	0.76

2536 at 3% O2 - Unheated					2541 at 3% O2 - Unheated				
	15-Oct	18-Oct	Delta	% Change		15-Oct	18-Oct	Delta	% Change
9.5	0.7392	0.7839	0.0447	6.05	9.5	0.8510	0.8749	0.0239	2.81
50	0.8401	0.8921	0.0520	6.18	50	0.9675	1.0043	0.0368	3.80
100	0.8955	0.9467	0.0511	5.71	100	1.0201	1.0617	0.0415	4.07
500	1.0562	1.1056	0.0494	4.68	500	1.1782	1.2402	0.0619	5.26
1000	1.1440	1.2230	0.0790	6.90	1000	1.3051	1.3711	0.0660	5.06
2000	1.2555	1.3276	0.0722	5.75	2000	1.3881	1.4050	0.0170	1.22
5000	1.2953	1.3570	0.0617	4.77	5000	1.4133	1.4314	0.0181	1.28
8000	1.3073	1.3692	0.0619	4.73	8000	1.4245	1.4432	0.0187	1.32
10000	1.3117	1.3740	0.0624	4.76	10000	1.4292	1.4479	0.0188	1.31

2536 at 5% O2 - Unheated					2541 at 5% O2 - Unheated				
	15-Oct	18-Oct	Delta	% Change		15-Oct	18-Oct	Delta	% Change
9.5	0.7261	0.7740	0.0479	6.59	9.5	0.8470	0.8628	0.0158	1.87
50	0.8180	0.8730	0.0550	6.72	50	0.9453	0.9829	0.0376	3.98
100	0.8804	0.9261	0.0456	5.18	100	1.0126	1.0385	0.0260	2.56
500	1.0241	1.0806	0.0565	5.52	500	1.1542	1.2091	0.0549	4.76
1000	1.1131	1.1741	0.0611	5.49	1000	1.2447	1.3514	0.1066	8.57
2000	1.2295	1.3240	0.0945	7.68	2000	1.3826	1.4053	0.0227	1.64
5000	1.2939	1.3581	0.0642	4.96	5000	1.4167	1.4337	0.0170	1.20
8000	1.3070	1.3708	0.0638	4.88	8000	1.4264	1.4458	0.0194	1.36
10000	1.3117	1.3757	0.0640	4.88	10000	1.4309	1.4506	0.0197	1.38

The FETS were heated for a calibration run on October 16, 1998.

Table 9. Comparison of unheated calibration results when the FETs were not heated in between.

2536 at 0% O2 - Unheated					2541 at 0% O2 - Unheated				
	18-Oct	21-Oct	Delta	% Change		18-Oct	21-Oct	Delta	% Change
9.5	1.1930	1.1769	-0.0161	-1.35	9.5	1.2643	1.2037	-0.0606	-4.79
50	1.2461	1.2784	0.0324	2.60	50	1.3194	1.3399	0.0205	1.55
100	1.2647	1.3020	0.0373	2.95	100	1.3380	1.3656	0.0276	2.07
500	1.3012	1.3374	0.0363	2.79	500	1.3750	1.4021	0.0271	1.97
1000	1.3176	1.3528	0.0352	2.67	1000	1.3915	1.4182	0.0268	1.92
2000	1.3336	1.3676	0.0340	2.55	2000	1.4075	1.4338	0.0263	1.87
5000	1.3544	1.3869	0.0325	2.40	5000	1.4282	1.4535	0.0254	1.77
8000	1.3657	1.3969	0.0312	2.29	8000	1.4395	1.4641	0.0246	1.71
10000	1.3701	1.4011	0.0310	2.26	10000	1.4440	1.4682	0.0242	1.68

2536 at 3% O2 - Unheated					2541 at 3% O2 - Unheated				
	18-Oct	21-Oct	Delta	% Change		18-Oct	21-Oct	Delta	% Change
9.5	0.7839	0.8285	0.0446	5.69	9.5	0.8749	0.8933	0.0184	2.10
50	0.8921	0.9134	0.0213	2.39	50	1.0043	1.0032	-0.0011	-0.10
100	0.9467	0.9667	0.0200	2.12	100	1.0617	1.0626	0.0009	0.08
500	1.1056	1.1094	0.0038	0.34	500	1.2402	1.2315	-0.0087	-0.70
1000	1.2230	1.2017	-0.0213	-1.74	1000	1.3711	1.3823	0.0112	0.81
2000	1.3276	1.3532	0.0256	1.93	2000	1.4050	1.4249	0.0199	1.41
5000	1.3570	1.3847	0.0277	2.04	5000	1.4314	1.4520	0.0206	1.44
8000	1.3692	1.3967	0.0276	2.02	8000	1.4432	1.4637	0.0205	1.42
10000	1.3740	1.4015	0.0274	2.00	10000	1.4479	1.4686	0.0207	1.43

2536 at 5% O2 - Unheated					2541 at 5% O2 - Unheated				
	18-Oct	21-Oct	Delta	% Change		18-Oct	21-Oct	Delta	% Change
9.5	0.7740	0.8210	0.0470	6.08	9.5	0.8628	0.8856	0.0227	2.64
50	0.8730	0.8998	0.0268	3.07	50	0.9829	0.9867	0.0037	0.38
100	0.9261	0.9504	0.0243	2.62	100	1.0385	1.0454	0.0069	0.67
500	1.0806	1.0887	0.0080	0.74	500	1.2091	1.2076	-0.0016	-0.13
1000	1.1741	1.1711	-0.0030	-0.26	1000	1.3514	1.3191	-0.0323	-2.39
2000	1.3240	1.3466	0.0227	1.71	2000	1.4053	1.4238	0.0185	1.32
5000	1.3581	1.3854	0.0272	2.01	5000	1.4337	1.4538	0.0200	1.40
8000	1.3708	1.3979	0.0271	1.97	8000	1.4458	1.4659	0.0201	1.39
10000	1.3757	1.4026	0.0269	1.95	10000	1.4506	1.4704	0.0198	1.37

Variation Between Parts

Supposedly identical FETs show considerable variation in threshold voltages. As a result, it is not possible simply to take out a failed FET, and replace it with a new FET, without recalibrating and adjusting the signal conditioning zero and span.

For example, Table 10 lists the FET voltages that would have to be signal conditioned for the 2 FETs used in the Add-On boards. It can be seen that the span does not vary too much from FET to FET, but the zero does.

Suppose the signal conditioning was adjusted to convert the FET 2536 output to the 0.4 to 1.4 volts required by the analog to digital converter. If FET 2536 failed, and was replaced by FET 2541 without rezeroing the signal conditioning, the board output in a 0% oxygen atmosphere would indicate that the hydrogen concentration was always below 10 ppm when in reality it was varying between 10 and 10,000 ppm. At 20% oxygen, the two ranges would overlap some, but the readings would be considerably off.

Table 10. FET Threshold Voltages

	FET 2536			FET 2541		
	10 ppm	10,000 ppm	Span	10 ppm	10,000 ppm	Span
0% Oxygen	2.65 V	2.59 V	0.06 V	2.70 V	2.64 V	0.06 V
20% Oxygen	2.83 V	2.59 V	0.24 V	2.90 V	2.64 V	0.26 V

Note: Both FETs are driven by a constant current source of 100 micro-amps

Temperature Sensitivity

The design of the Hydrogen Sensor Board included features to minimize the sensitivity to temperature. However, the Hydrogen Sensor Board output was still sensitive to temperature. In order to compensate for temperature influences, the Hydrogen Sensor Board was operated in an oven capable of providing an accurate and constant temperature. The Hydrogen Sensor Board was held at 30, 50, 70, 90, and 130°F for an hour each. The Hydrogen Sensor Board output was monitored by a small telemetry package as shown in Figure 27 and radioed to a receiver. The Hydrogen Sensor Board output was converted to 0 to 256 counts by the telemetry package. The data is shown plotted in Figure 28.

Figure 27. Temperature Sensitivity Testing of the Hydrogen Sensor Boards

Figure 28. Effect of Temperature on the Hydrogen Sensor Board Output.

The effect of temperature variations on output is nearly linear and can be described by the equation:

$$T = 1.7808\text{Cnt} - 291.8971$$

where

T = temperature, deg. F

Cnt = Hydrogen Sensor Board output in counts

Counts are related to volts by the following equation:

$$V = \frac{\text{Cnt}}{255} + 0.4$$

where

V = Hydrogen Sensor Board output in volts

Cnt = Hydrogen Sensor Board output in counts

Overall, the Hydrogen Sensor Board sensitivity to temperature was 2.2 mV per degree Fahrenheit. In Table 10, the typical span of the hydrogen FET output from 10 to 10,000 ppm of hydrogen concentration in a non-oxygen atmosphere is about 60 mV. After amplification by the signal conditioning, the change in Hydrogen Sensor Board output over a 10 to 10,000 ppm hydrogen concentration variation is 252 mV. The total range of hydrogen measurement is equivalent to about a 110°F change in temperature. Therefore, temperature can have a very large influence on the hydrogen reading and must be compensated for during data processing.

Response Time

Concerns were voiced regarding sluggish response or non-response of the unheated FET to changes in hydrogen concentration. Therefore, it was decided to create the hydrogen sensor board incorporating options for operating the FET heaters as well as signal conditioning for the FET output.

Heating of the Robust Hydrogen Sensor serves to improve the response time of the hydrogen FET to a change in hydrogen concentration, particularly a decreasing hydrogen concentration. The actual effect in response time due to heating the hydrogen sensors was evaluated during the calibration testing.

Figure 29 shows the maximum rate of response for a series of step changes in hydrogen concentration over a range of constant oxygen concentrations. In no case is the rate of response of the heated hydrogen FET considerably different from an unheated hydrogen FET.

Since the hydrogen FETs were tested in a chamber about 0.125 cubic feet in volume, the free volume of the chamber may largely control the rate of response. However, the intended application is to have the hydrogen FET enclosed in a volume to monitor slow changes in hydrogen concentration over long periods of time. So the test setup should give a reasonable relative value between heating and not heating the hydrogen FET.

Based on the observed responses, it was decided that there was no value in heating the hydrogen FETs intermittently or continuously.

Figure 29. Comparison of Hydrogen Sensor Response Rate Between Hot and Cold Operation.

Conclusions and Recommendations

A low-power signal conditioning and heater control board was fabricated for the Sandia Robust Hydrogen Sensor. It has been found that:

1. Power consumption of the FET excitation and signal conditioning circuitry was $<200\mu\text{A}$ (excluding 1.3mA for the timer optoisolator).
2. The response of the hydrogen FET to hydrogen is noticeably different when oxygen is and is not present.
3. When in the presence of oxygen, a single calibration curve can be developed to determine the hydrogen concentration if the hydrogen FET threshold voltage and oxygen concentration is known.
4. Some hydrogen FETs show marked shifts in their performance after they have been heated and then cooled. It is recommended that the hydrogen FETs be operated unheated.
5. The response of the hydrogen FETs tested to a step change in hydrogen level is not significantly different between heated and unheated operation when the sensors are in an enclosure with free volume. It is recommended that the hydrogen FETs be operated unheated to reduce power consumption.
6. The hydrogen FETs tested had the same threshold voltage change over a 10 ppm to 10,000 ppm hydrogen concentration range. However, the absolute voltage ranges were quite different. Until hydrogen FETs become much more uniform in their response, each hydrogen FET will have to be calibrated prior to service. A standard calibration curve is not possible.
7. The hydrogen FET output, along with the signal conditioning, is noticeably sensitive to temperature. The hydrogen FET and its signal conditioning must be characterized for temperature response so this may be eliminated during data processing.

References

1. B. M. Mickelsen, G. R. Laguna, and M. R. Daily, "Integrated Nuclear Material Monitor", Proceedings of the 38th Annual Meeting of the Institute of Nuclear Materials Management, July 1997.
2. R.C. Hughes, D.J. Moreno, M.W. Jenkins, and J.L. Rodriguez, "The Response of the Sandia Robust Wide Range Hydrogen Sensor to H₂-O₂ Mixtures", 1994 Solid-State Sensor and Actuator Workshop, June 13-16, Hilton Head Island, SC.
3. I. Lundstöm, "Hydrogen Sensitive MOS-Structures Part 1: Principles and Applications", Sensors and Actuators, I, 403, (1981).
4. Personal communication with M. Jenkins and Larry Anderson, Microsensor R&D Department, 1999.
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APPENDIX A – Initial Specifications

General:

The INuMM ESP contains the power source, power switching circuitry, multiplexer, A/D converter, and RF communications for operating the H₂ FET and reporting its output value. The ESP power source is inadequate to run the power FETs on the H₂ sensor chip which serve as heaters to clean up the H₂ FET by driving the hydrogen out of its junction. Therefore, the power FET heaters will be powered by a power supply external to the AF&F.

A separate add-on board containing circuitry for signal conditioning the H₂ FET output and for controlling the power FET heaters is required. The add-on board may have to perform power conditioning in order to correctly power the H₂ FET.

Statement of Work:

1. All parts and labor to be supplied or procured by Department 1738.
2. Select 4 functional hydrogen sensors.
3. Design H₂ FET power supply/signal conditioning circuit. The H₂ FET and its signal conditioning are to be powered by the battery in the ESP. Power supplied by the ESP to the add-on board is 3.6 volts (direct battery voltage) and is limited to a maximum current draw of 3 mA. The 3 mA current is broken down as follows:

2 mA for the H₂ FET and signal conditioning

1 mA for the heater control

An alternative voltage for powering only the H₂ FET is 7.2 volts supplied by a voltage doubling circuit. If 7.2 volts is required to power the H₂ FET, it is preferred that the voltage doubling circuit be part of the add-on board rather than using the voltage doubling circuit of the ESP.

Coordinate with Larry Sheets, AS/FM&T, and Scott Kuszmaul, SNL/NM, on where to tap into the ESP circuits. Nominal wiring is per Figure 10.

Scale the H₂ FET output to match A/D input range as follows:

0.4 V = 0 ppm H₂ concentration

1.4 V = 5000 ppm H₂ concentration

Please verify A/D input range with Scott Kuszmaul, 2338.

Noise on the output signal caused by the signal conditioning should be less than 2mV. Noise level will be measured during testing.

Provide 12-inch long 24 gauge Teflon coated stranded wire connections per interface drawing in Figure 10.

4. Design a heater control circuit to provide closed-loop control which, when powered by externally supplied 3.6 V ($\pm 0.5V$) and the FET Power line is at 0V ($\pm 0.5V$), will maintain the H₂ FET temperature at 180 degrees centigrade for 15 minutes, and then switch off the heater power.

The heater will remain off until the FET Power line goes to 3.6V ($\pm 0.5V$), resetting the heater control circuit, which then switches on the heater power when the FET Power line goes to 0V ($\pm 0.5V$). The event/time sequence for the heat operation is shown below:

Consult with Bob Hughes, 1315, to verify the heater on time that will clean the H₂ FET and ready it for the next sample, the heater temperature set point, and for other details regarding the hydrogen sensor.

Figure A-1. Power FET Heater Power Control Sequence

The heater control circuit cannot draw more than 1 mA from the H₂ FET Power line.

The heater circuit shall have a mechanical switch, which, when activated, will bypass the heater timing control described above, and continuously power the heaters via the temperature feedback loop.

Consult with Scott Kuszmaul, 2338, as required to define interfaces with the current production ESP, functioning of the ESP, and to obtain sample schematics for H₂ FET circuits.

Modifications to any ESPs will be performed by AS/FM&T.

Provide 12-inch long, 24 gauge Teflon coated stranded wire connections for the heater external power per interface drawing in Figure 10.

5. Build 4 circuit boards containing these circuits. Boards with components loaded and protective enclosure installed must fit in a volume 0.5" high and having a form which fits within the boundaries defined by Figure 11. The protective enclosure need only protect against accidental electrical contact with the add-on board, and damage to parts due to normal handling.
6. Load components on 2 circuit boards. Test to verify operation of FET signal conditioning and heater control circuit. The remaining 2 circuit boards are reserve.
7. Support calibration of 2 H₂ Sensor Add-On boards.

Deliverables:

1. 2 assembled Hydrogen Sensor Add-On boards with protective packaging, tested and ready for calibration on September 1, 1998.
2. Testing support for Hydrogen Sensor Add-On board calibration and rework support to fix or alter boards to function correctly if problems are found during calibration.

3. The following items delivered to Scott Faas on or before September 30, 1998:
- a. 2 bare Hydrogen Sensor Add-On boards.
 - b. 2 tested hydrogen sensors, or the remaining hydrogen sensors of the 4 that were tested and verified functional in Statement of Work, task 1.
 - c. B size drawings of Hydrogen Sensor Add-On board layout and circuit diagram.
 - d. Data files of the Hydrogen Sensor Add-On board layout and circuit diagram. Format of delivery media TBD.

Figure A-2. Hydrogen Sensor Add-On Board Interfaces

Figure A-3. Maximum Area Allocated for Add-On Board.

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Appendix B

Version 2 Hydrogen FET Bias Circuit

Figure B-1 shows the schematic of the hydrogen FET and the opamp current regulator. In this design the opamp monitors the current through the hydrogen FET via the current sensing resistor R41. In this design setting the current is easy – simply adjust the reference voltage going to the positive leg of the opamp (R43). Not only is current adjustment easy but the temperature coefficient of this source is near the best temperature coefficient obtainable from the LM134. This is because the current depends only on the temperature coefficient of the resistor (which can be 10ppm) and the temperature coefficient of the reference voltage (3-10ppm). Together these two temperature coefficient values yield a total temperature coefficient comparable to the LM134 at its best. Alas, the circuit has one drawback; the voltage developed across the current sense resistor gets added to the threshold voltage, V_{th} , of the hydrogen FET which makes the overall circuit somewhat harder to setup since you have a constant offset to deal with. This is not really a problem, it just means you need to think in terms of $V_{th} + \text{offset}$ instead of V_{th} . If you view the output from this first opamp (U3-1) you will need to remember that the offset is present.

Several other things to note about this circuit. First the hydrogen FET drain/gate voltage is the output of the U3-1 opamp. While the controller will work with the drain tied to a fixed voltage and the gate tied to the output of U3-1, the response would then also be a function of the variability of the fixed voltage.

Figure B-1. Version 2 Hydrogen FET Biasing Circuit Schematic

In this application the fixed voltage is the doubler output which changes with time. This produces a significant change in the V_{th} measurement and cannot be tolerated. Tying the drain/gate to the output of U3-1 makes the response only a function of the FET current (and of course the hydrogen concentration). Also note that the circuit board was designed to configure either the LM134 or the current controller above. The jumpers JP1-JP4 are used to select which current control method is used. JP1, JP3 and JP4 are shown installed for the method discussed above. The rest of the circuitry on the version 2 board is the same as the version 1 board except for the addition of R42 and R43 which are used to set the current hydrogen FET current as discussed above.

Appendix C

Data Tabulations

Table C-1. Calibration Data for FETs 2536 and 2541

FET 2536

0% Oxygen			3% Oxygen			5% Oxygen			20% Oxygen		
H ₂ conc., ppm	Signal, volts	Signal, counts	H ₂ conc., ppm	Signal, volts	Signal, counts	H ₂ conc., ppm	Signal, volts	Signal, counts	H ₂ conc., ppm	Signal, volts	Signal, counts
9.5	0.980572	148	9.5	0.678886	71	9.5	0.667837	68	8.0	0.643047	62
50	1.09648	178	50	0.799342	102	50	0.768779	94	50	0.714157	80
100	1.12667	185	100	0.886565	124	100	0.84905	115	100	0.783077	98
500	1.16993	196	500	1.10012	179	500	1.03715	162	500	0.941603	138
1000	1.18325	200	1000	1.16641	195	1000	1.13431	187	1000	0.99251	151
2000	1.20074	204	2000	1.1988	204	2000	1.19794	203	2000	1.07585	172
5000	1.22339	210	5000	1.22633	211	5000	1.22871	211	5000	1.22132	209
8000	1.2361	213	8000	1.23934	214	8000	1.24189	215	8000	1.23962	214
10000	1.24762	216	10000	1.25088	217	10000	1.25336	218	10000	1.25284	217
8000	1.23959	214	8000	1.24167	215	8000	1.244	215	8000	1.24135	215
5000	1.22985	212	5000	1.23113	212	5000	1.23263	212	5000	1.22512	210
2000	1.2112	207	2000	1.20743	206	2000	1.20565	205	2000	1.05023	166
1000	1.19625	203	1000	1.17853	199	1000	1.09321	177	1000	0.979963	148
500	1.18593	200	500	1.06664	170	500	1.02197	159	500	0.941745	138
100	1.1546	192	100	0.864088	118	100	0.845706	114	100	0.806436	104
50	1.13799	188	50	0.812815	105	50	0.797569	101	50	0.760689	92
9.5	1.09956	178	9.5	0.688658	74	9.5	0.681322	72	9.5	0.658809	66

FET 2541

0% Oxygen			3% Oxygen			5% Oxygen			20% Oxygen		
H ₂ conc., ppm	Signal, volts	Signal, counts	H ₂ conc., ppm	Signal, volts	Signal, counts	H ₂ conc., ppm	Signal, volts	Signal, counts	H ₂ conc., ppm	Signal, volts	Signal, counts
9.5	1.1835	200	9.5	0.920912	133	9.5	0.906401	129	8.0	0.88978	125
50	1.24314	215	50	1.00614	155	50	0.9777	147	50	0.934729	136
100	1.26387	220	100	1.07144	171	100	1.04117	163	100	0.98151	148
500	1.29499	228	500	1.26063	219	500	1.22882	211	500	1.11551	182
1000	1.30455	231	1000	1.29489	228	1000	1.29042	227	1000	1.17306	197
2000	1.31719	234	2000	1.31597	234	2000	1.31744	234	2000	1.2811	225
5000	1.33377	238	5000	1.33569	239	5000	1.33807	239	5000	1.33453	238
8000	1.34343	241	8000	1.34557	241	8000	1.34767	242	8000	1.34675	241
10000	1.35212	243	10000	1.3543	243	10000	1.35628	244	10000	1.35611	244
8000	1.34641	241	8000	1.34758	242	8000	1.34925	242	8000	1.34808	242
5000	1.33932	240	5000	1.33977	240	5000	1.34137	240	5000	1.33761	239
2000	1.32527	236	2000	1.32268	235	2000	1.32295	235	2000	1.29198	227
1000	1.31428	233	1000	1.30498	231	1000	1.3006	230	1000	1.17151	197
500	1.30669	231	500	1.2816	225	500	1.23495	213	500	1.1273	185
100	1.28287	225	100	1.0661	170	100	1.04827	165	100	1.00211	154
50	1.27076	222	50	1.02194	159	50	1.00737	155	50	0.967717	145
9.5	1.241	214	9.5	0.922766	133	9.5	0.916778	132	9.5	0.897991	127

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