

Application of Smart Solid State Sensor Technology in Aerospace Applications

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Aerospace applications require a range of chemical sensing technologies to monitor conditions in both space vehicles and aircraft operations. One example is the monitoring of oxygen. For example, monitoring of ambient oxygen (O₂) levels is critical to ensuring the health, safety, and performance of humans living and working in space. Oxygen sensors can also be incorporated in detection systems to determine if hazardous leaks are occurring in space propulsion systems and storage facilities. In aeronautic applications, O₂ detection has been investigated for fuel tank monitoring. However, as noted elsewhere [1], O₂ is not the only species of interest in aerospace applications with a wide range of species of interest being relevant to understand an environmental or vehicle condition. These include combustion products such as CO, HF, HCN, and HCl, which are related to both the presence of a fire and monitoring of post-fire clean-up operations.

The ability to produce microsensor platforms which can be tailored to measure a range of species has been an ongoing technology direction of this group. Combined with that effort has been the development of miniaturized hardware and software systems ("Lick and Stick" technology) that can be implemented in aerospace applications [1]. These smart sensor systems include signal conditioning, data processing, power, and communication in a compact structure, for placement in multiple locations to improve the awareness of an environment.

Considerations related to potential implementation of this smart "Lick and Stick" sensor technology have gone into its design. Fundamental hardware configuration considerations include minimizing size, weight, power consumption; accommodating a range of power input supplies; and communication interfaces. Furthermore, operational considerations such as sensor operation temperature, capability to withstand changes in the ambient environment including high vacuum, time between calibration, and power consumption to reduce battery charging or replacement have strong roles to play in the viability of a sensor system to meet the needs of a given application.

This paper discusses the development of an electrochemical cell platform based on a polymer electrolyte, NAFION, and a three-electrode configuration. The approach has been to mature this basic platform for a range of applications and to test this system, combined with "Lick and Stick" electronics, for its viability to monitor an environment related to astronaut crew health and safety applications with an understanding that a broad range of applications can be addressed with a core technology.

In particular, O₂ sensor technology based on this NAFION-based electrochemical cell platform is being evaluated for International Space Station (ISS) environmental monitoring applications. Present liquid electro-

chemical cells currently deployed on the ISS do not meet the accuracy or calibration life requirements. It is considered that a solid state sensor approach might be able to avoid some of technology issues related to liquid based systems. A room temperature system has an advantage of reduced power consumption resulting in longer battery life.

The basic prototype room temperature electrochemical cell sensor structure is shown in Figure 1. The sensor structure has a three-electrode configuration with a NAFION electrolyte. Inlets to the sensor control the amount of gas reaching the electrodes from the outside environment. The sensor responds to a range of oxygen concentrations as seen in Figure 2. This figure shows sensor response both in ambient air and in concentrations ranging from 3% to 21% in a 200 sccm flowing stream. It is from this basic structure that attempts to miniaturize and test the oxygen sensors system have been on-going. These tests include measurements. The sensors were evaluated at the White Sands Test Facility on their ability to accurately detect O₂ concentrations over a range of pressures and oxygen concentrations. Further work has integrated the oxygen sensor into the "Lick and Stick" electronics platform with wireless capability. The ability to instrument a room with a wirelessly data feed to a central location for display or recording has been demonstrated using proof-of-concept hardware. Each sensor output was available individually and could be correlated to variables including location and airflow to understand the complex environment of a spacecraft cabin. Results of these demonstrations and testing will be presented.

It is concluded that this approach has a range of applications. Modifying the basic NAFION sensor structure can allow the detection of other species such as HF, HCN and HCl. The overall approach of a distributed wireless system has applications not only in environmental monitoring but anywhere a deployable standalone gas monitoring system might be required. These areas include pre and post fire monitoring and leak detection. Actual implementation in a given environment depends on repeatable demonstrate in relevant environments of the sensor systems ability to meet application requirements.

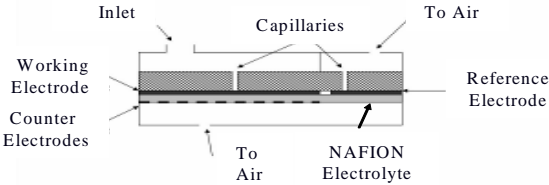


Figure 1. First Generation NAFION O₂ Sensor Structure.

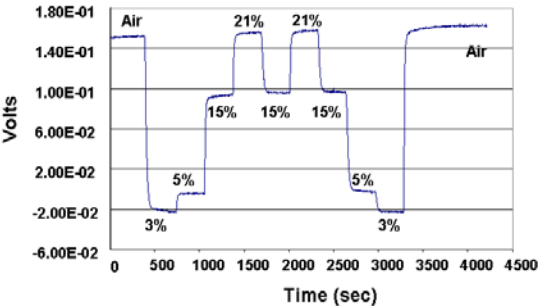


Figure 2. NAFION electrochemical cell sensor response to various oxygen concentrations.

Reference 1: G. W. Hunter, C. C. Liu, and D. Makel (2006) "Microfabricated Chemical Sensors for Aerospace Applications", in Gad-el-Hak, M ed. MEMS Handbook 2 edn, Design and Fabrication, CRC Press LLC, Boca Raton, Chapter 11.

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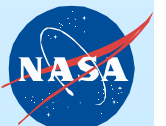
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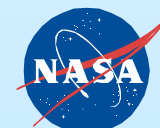
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OUTLINE

- **INTRODUCTION**
- **MICROFABRICATED GAS SENSORS**
- **AEROSPACE APPLICATION NEEDS**
 - **INTERNATIONAL SPACE STATION (ISS)**
 - **CEV FIRE DETECTION**
- **NAFION PLATFORM SENSOR DEVELOPMENT**
 - **EXTENDED O₂ SENSOR TESTING**
 - **HCN AND HCI SENSOR DEVELOPMENT**
- **“LICK AND STICK” HARDWARE DEVELOPMENT**
- **SUMMARY**



BASE PLATFORM SENSOR TECHNOLOGY

*Integration of Micro Sensor Combinations
into Small, Rugged Sensor Suites*

*Example Applications: AEROSPACE VEHICLE FIRE, FUEL, EMISSIONS,
ENVIRONMENTAL MONITORING, CREW HEALTH, SECURITY*

**Multi Species Fire Sensors
for Aircraft Cargo Bays**

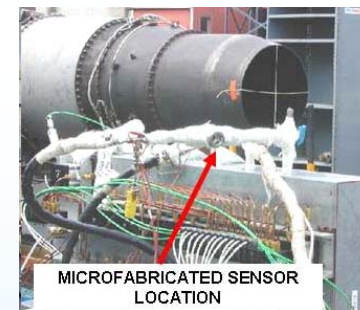
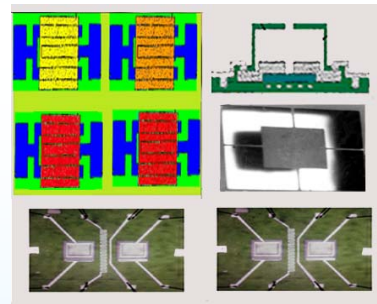


Microfabricated Fire
Detection Sensors

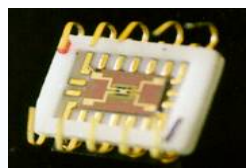
**“Lick and Stick” Space Launch Vehicle
Leak Sensors with Power and Telemetry**



**Aircraft Propulsion Exhaust High
Temperature Electronic Nose**



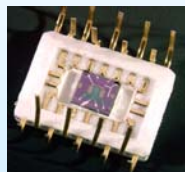
MICROFABRICATED SENSOR
LOCATION



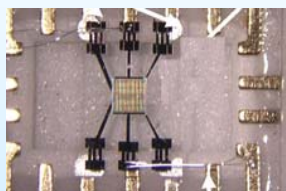
Oxygen Sensor



SiC Hydrocarbon
Sensor



H2 Sensor

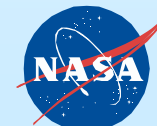


Nanocrystalline Tin
Oxide NOx and CO
Sensor



**Sensor Equipped
Prototype Medical
Pulmonary Monitor**

**Hydrazine EVA Sensors
(ppb Level Detection)**



Micro-Fabricated Gas Sensors for Low False Alarms

2005 R&D 100 AWARD WINNER

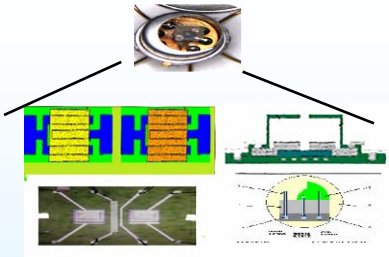
NASA 2005 TURNING GOALS INTO REALITY AA'S CHOICE AWARD

- **DECREASE CARGO BAY FALSE ALARM RATE AS HIGH AS 200:1**
- **APPROACH: COMBINED MEMS-BASED CHEMICAL SPECIES AND PARTICULATE ORTHOGONAL DETECTION AND CROSS-CORRELATION SIGNIFICANTLY REDUCES FALSE ALARMS**
- **FAA CARGO BAY FIRE TESTING: NO FALSE ALARMS/CONSISTENT FIRE DETECTION**

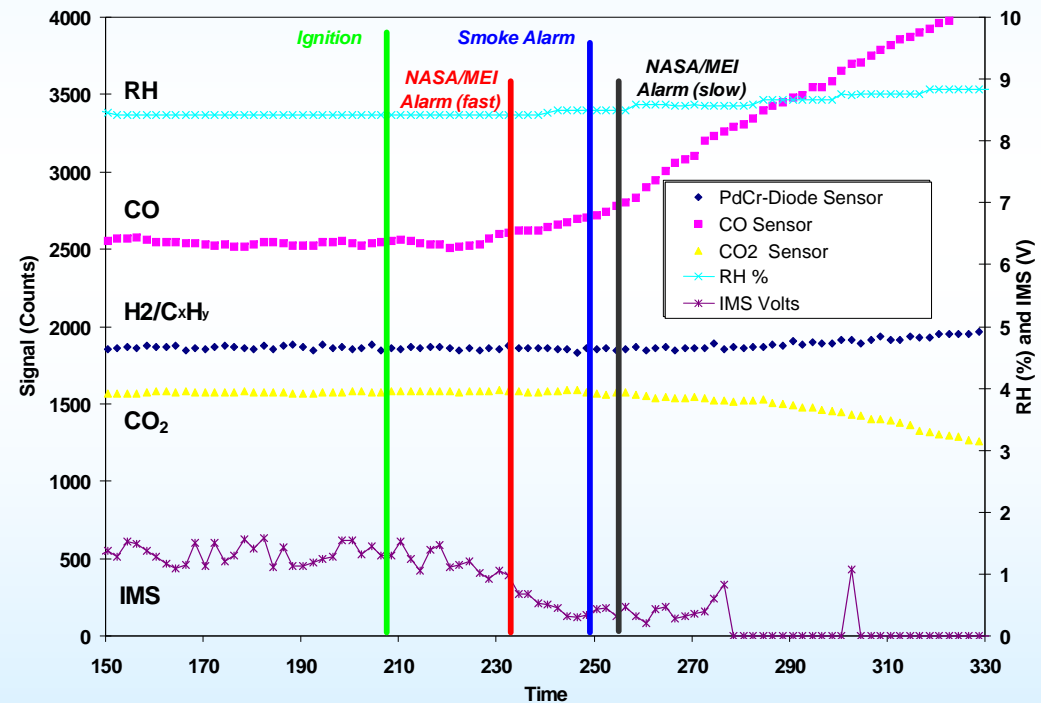
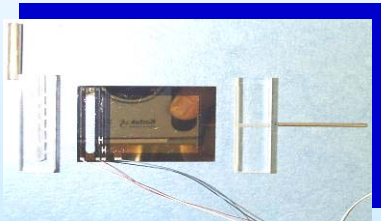
FAA Cargo Bay Testing



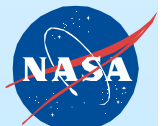
MEMS-Based Chemical Species Detection



MEMS-Based Particulate Detector

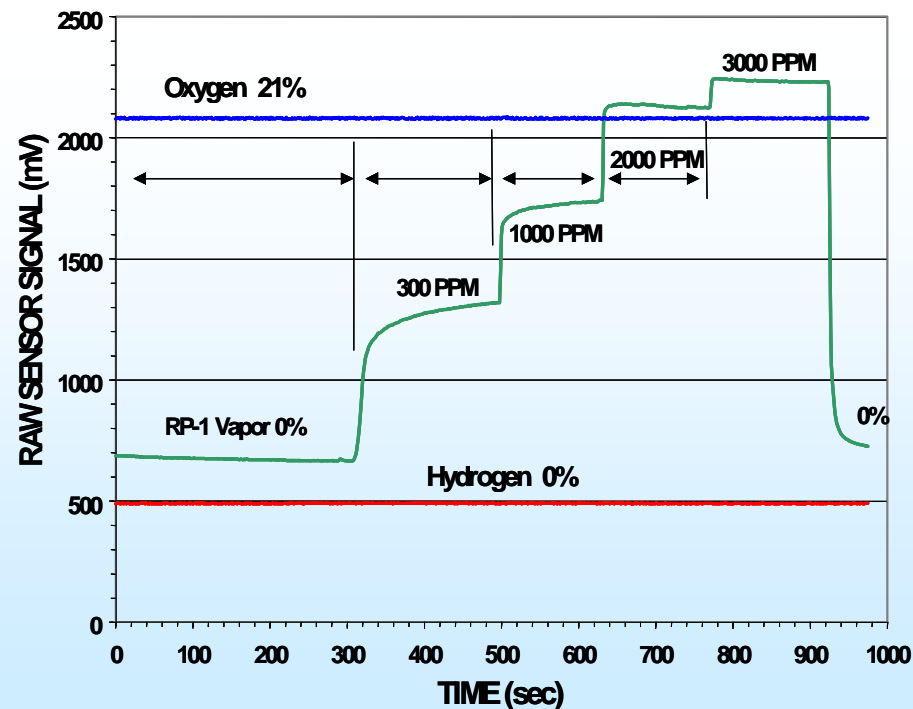
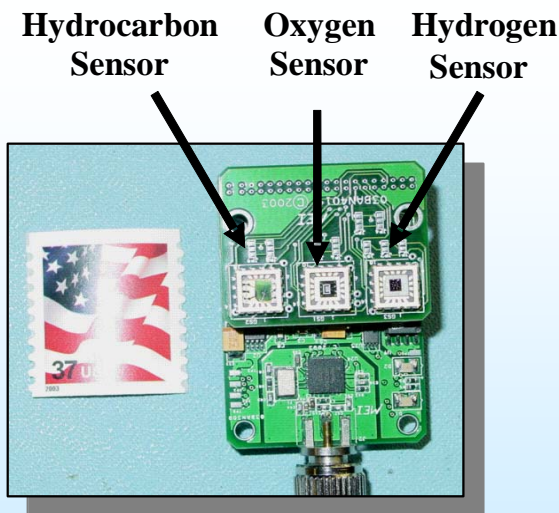


Makel Engineering, Inc.



“LICK AND STICK” LEAK SENSOR SYSTEM DEMONSTRATION

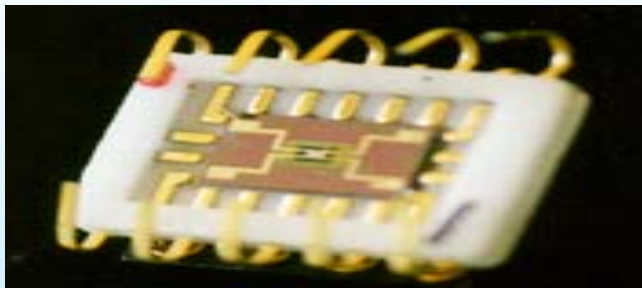
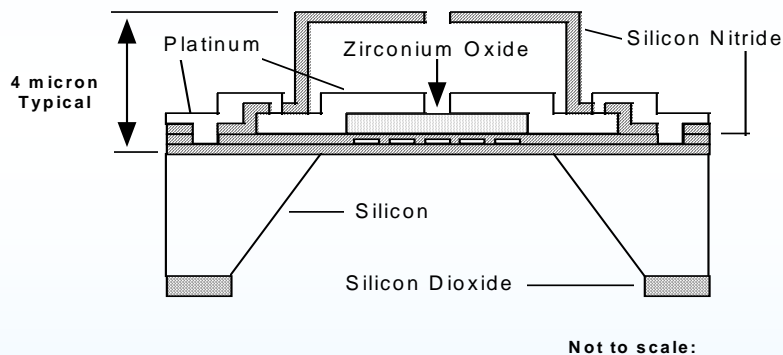
- COMBINE FUEL (HYDROGEN, HYDROCARBON) WITH OXYGEN IN AN ARRAY: DETERMINE EXPLOSIVE COMBINATIONS
- BASELINE: ZIRCONIA BASED O₂ SENSOR (ALTHOUGH NAFION BASED ROOM TEMPERATURE SYSTEM BEING MATURED FOR USE)
- SENSORS, POWER, DATA PROCESSING AND TELEMETRY SELF-CONTAINED IN NEAR THE SIZE OF A POSTAGE STAMP SYSTEM
- BEEN QUALIFIED FOR CREW LAUNCH VEHICLE APPLICATIONS (HARDWIRED) FOR HYDROGEN DETECTION ONLY
- LONGEVITY OF SENSOR SYSTEM LIFE ON A BATTERY IS A LIMITATION



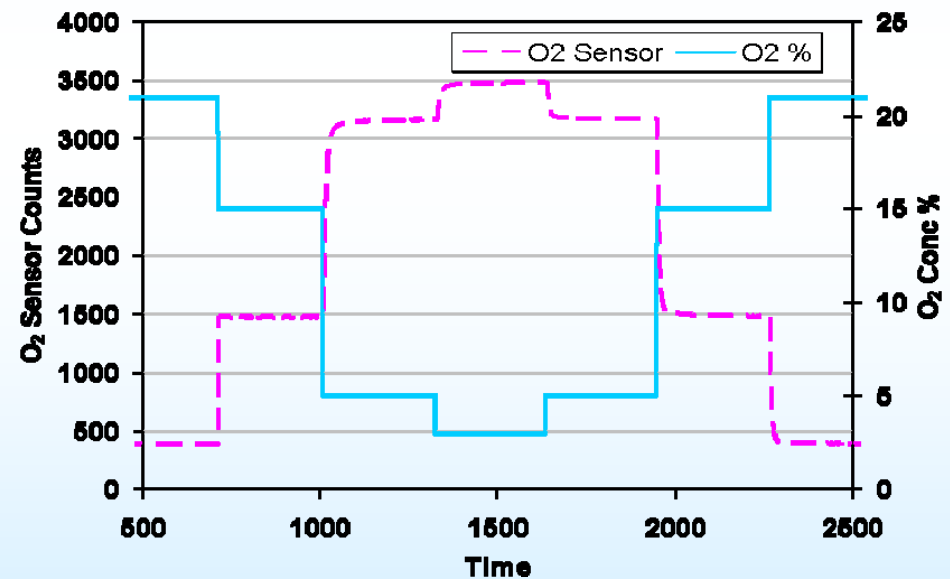
MICROFABRICATED OXYGEN SENSOR TECHNOLOGY



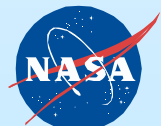
- MICROFABRICATED AND MICROMACHINED FOR MINIMAL SIZE, WEIGHT AND POWER CONSUMPTION (NEAR 100 mW FOR ~500 C OPERATION)
- AMPEROMETRIC OPERATION ALLOWS MEASUREMENT OF OXYGEN OVER A WIDE CONCENTRATION RANGE (0-100%)
- CHAMBER STRUCTURE CONTROLS OXYGEN DIFFUSION RATE
- RELATIVELY MATURE TECHNOLOGY WHOLE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



ZrO₂ Oxygen Sensor

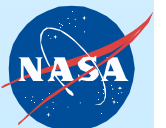


Zirconia Based Oxygen Microsensor Response To Various Oxygen Concentrations



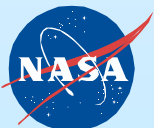
ISS ENVIRONMENTAL APPLICATIONS

- **CURRENT PORTABLE ENVIRONMENTAL MONITORS FOR OXYGEN AND COMBUSTION PRODUCT MONITORING ARE BASED ON LIQUID BASED ELECTROCHEMICAL SENSORS**
- **THESE SENSORS TYPICALLY HAVE LIMITED CALIBRATION LIFE AND DO NOT MEET THE CURRENT NEEDS OF ISS OR THE FUTURE NEEDS FOR EXPLORATION**
- **MAJOR ISSUE REVOLVES AROUND INTEGRITY OF THE SEALS AND MEBRANE OF LIQUID ELECTROCHEMICAL CELL AS PRESSURE IS VARIED. IT APPEARS THAT THE MEMBRANE TENSION IS PERMANENTLY IMPACTED BY PRESSURE VARIATIONS.**
- **SOLID-STATE SENSORS MAY HAVE ADVANTAGES DUE TO LACK OF LIQUID CELLS BUT MUST PROVE VIABILITY**
- **APPLICATIONS IS A CRIT 1 FUNCTION RELATED TO CREW AND VEHICLE SAFETY. REQUIREMENTS INCLUDE:**
 - **HIGH DEGREE OF CERTAINTY OF MEASUREMENT COUPLED WITH HIGH ACCURACY**
 - **MUST BE ABLE TO OPERATE IN A RANGE OF O2 CONCENTRATIONS**
 - **COMPENSATION FOR VARYING PRESSURES**
 - **STABLE CALIBRATION FOR SIGNIFICANT PERIODS OF TIME (MONTHS OR YEARS)**



EXPLORATION FIRE DETECTION APPLICATIONS

- **SOLID-STATE CHEMICAL SENSORS AGAIN MAY HAVE ADVANTAGES**
- **AS IN AERO APPLICATIONS, COMBINATION WITH PARTICULATE DETECTION MANDATORY**
- **APPROACHES RELATED TO REDUCTION OF AIRCRAFT CARGO BAY FALSE ALARMS RELEVANT TO FUTURE EXPLORATION MISSIONS**
- **MULTIPARAMETER DETECTION TO ALLOW BETTER UNDERSTANDING OF THE ENVIRONMENT**
 - **CO AND CO₂ STILL FUNDAMENTAL QUANTITIES TO MEASURE**
 - **OTHER SPECIES SUCH AS HYDROGEN/HYDROCARBONS, OXYGEN, AND HUMIDITY CONTINUE TO BE RELEVANT**
 - **ADDITIONALLY, HCl AND HCN RELEVANT FOR PREFIRE CONDITIONS**
- **MINIMAL SIZE, WEIGHT, AND POWER CONSUMPTION CONTINUE TO BE ISSUES ASSOCIATED WITH ANY AIRCRAFT AND SPACE FLIGHT APPLICATION**
 - **“LICK AND STICK” TECHNOLOGY BEING QUALIFIED FOR CREW LAUNCH VEHICLE APPLICATIONS**
 - **BASIC APPROACH RELEVANT FOR EXPLORATION FIRE AND ISS IN ENVIRONMENTAL MONITORING APPLICATIONS**
- **CO DETECTION DOWN TO PPM LEVEL ALSO REQUIRED FOR ENVIRONMENTAL MONITORING APPLICATIONS**



BASE TECHNOLOGY PLATFORMS ADDRESS MULTIPLE NEEDS

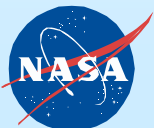
SENSOR PLATFORM

- **NAFION BASED ELECTROCHEMICAL CELL**
 - **ROOM TEMPERATURE OPERATION ALLOWS EXTENDED BATTERY-POWERED “LICK AND STICK” SENSOR SYSTEM OPERATION**
 - **VARIATION IN ELECTRODE STRUCTURE AND OPERATING PARAMETERS ALLOW DETECTION OF A RANGE OF SPECIES**
- **O₂, HCl, AND HCN SENSORS BEING DEVELOPED BASED ON NAFION PLATFORM**
 - **ADDRESS ISS ENVIRONMENTAL AND CEV FIRE DETECTION APPLICATIONS**
 - **SAME BASIC PLATFORM/PACKAGING USED FOR THREE SENSOR TYPES**

HARDWARE PLATFORM

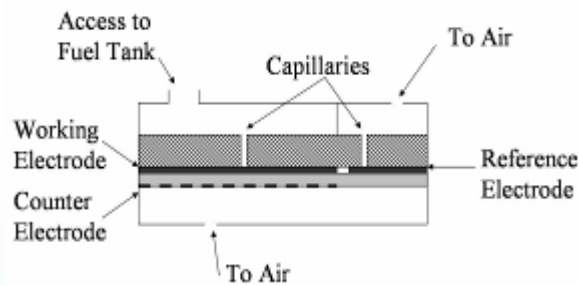
- **“LICK AND STICK” SMART SENSOR PLATFORM BEING SPACE QUALIFIED**
 - **ADAPTABLE TO WIRED/WIRELESS COMMUNICATION; WIRED OR BATTERY POWER; MULTIPLE SENSOR INPUT CONFIGURATIONS**
 - **SPACE QUALIFICATION OF CORE SYSTEM INCREASES POSSIBLE FLIGHT READINESS OF FUTURE SYSTEMS**

THIS PRESENTATION DISCUSSES DEVELOPMENT OF BOTH THE NAFION SENSOR PLATFORM AND “LICK AND STICK” HARDWARE PLATFORM FOR SPACE APPLICATIONS.

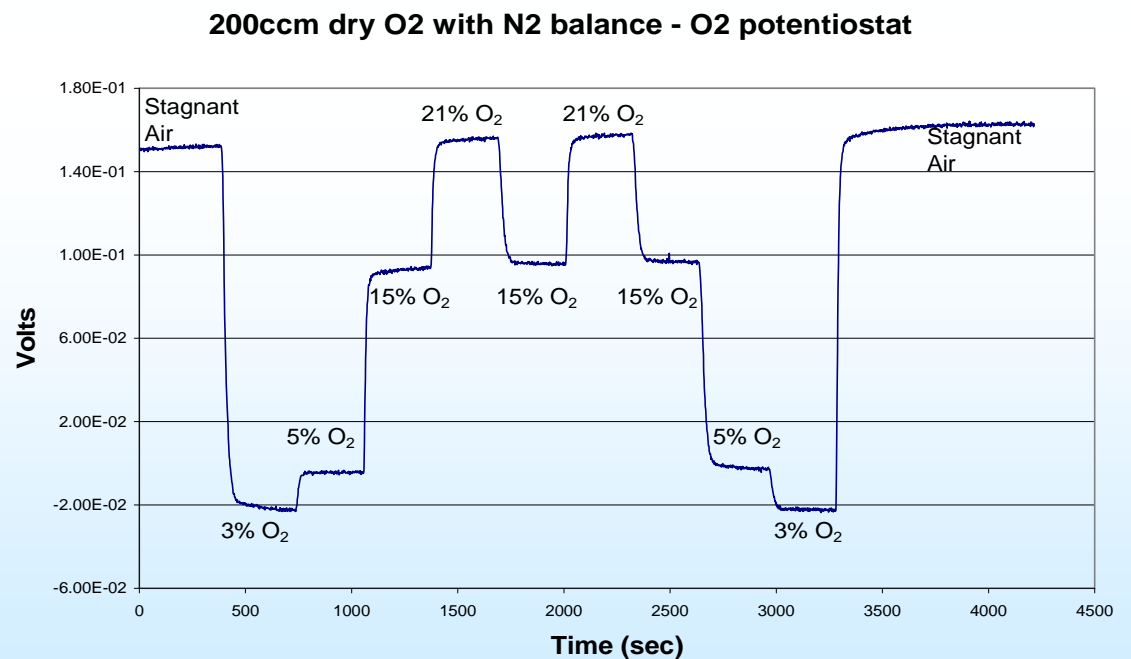


ROOM TEMPERATURE O₂ SENSOR TECHNOLOGY

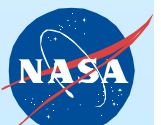
- POSSIBLE REPLACEMENT FOR PRESENT LIQUID ELECTROCHEMICAL CELL TECHNOLOGY
- VIABILITY FOR SPACE BASED APPLICATIONS MUST BE VERIFIED THROUGH AN EXTENSIVE TEST PROGRAM.
- ONE SIGNIFICANT LESSON OF PREVIOUS ISS IMPLEMENTATION IS THAT TESTING IN RELEVANT ENVIRONMENTS OVER THE REQUIRED SENSOR LIFE IS MANDATORY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



NAFION O₂ Sensor Structure



Preliminary NAFION O₂ Sensor Data



WHITE SANDS TEST FACILITY O2 SENSOR TESTING

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

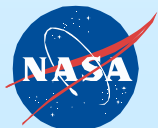
Present commercial
ISS O2 sensors



NAFION Sensors in
manifold

NAFION Sensors
Control Electronics

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



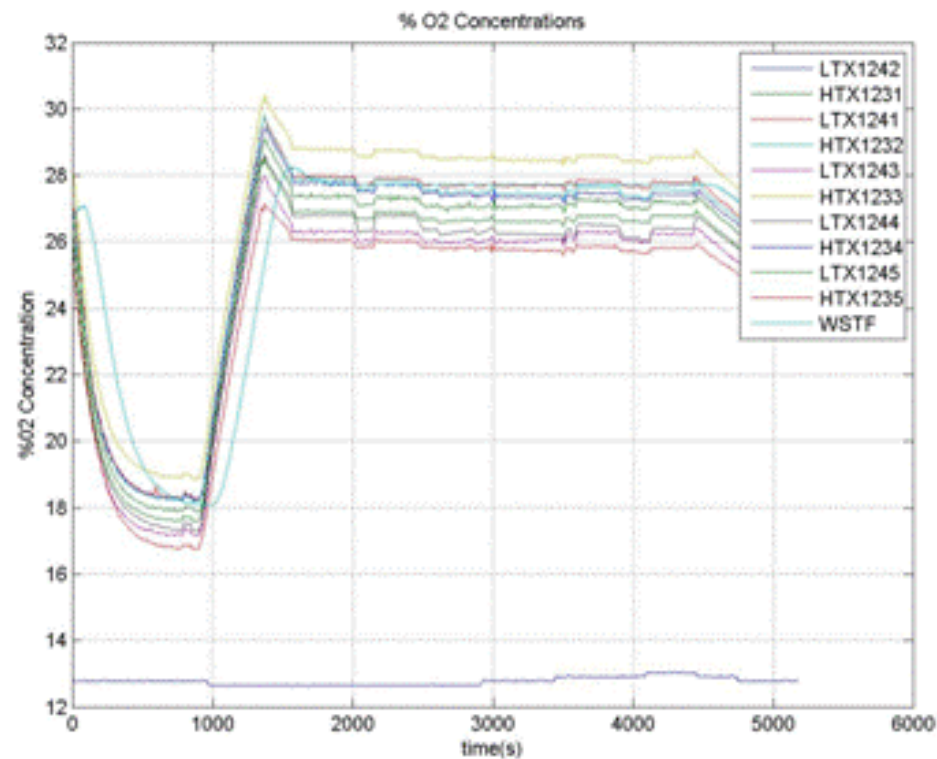
REPRESENTATIVE WHITE SANDS O2 TEST DATA (MIDDLE OF TESTING)

- DATA FROM BOTH HIGH TEMPERATURE O2 SENSOR AND ROOM TEMPERATURE O2 SENSORS SHOWN
- MAJOR ISSUES IN EARLIER TESTING:
 - AGREEMENT OF CALIBRATED SENSORS TO REFERENCE READING
 - MAINTAINING CALIBRATION OVER EXTENDED DURATIONS/TESTING
 - NEED TIGHT GROUPING IN SENSOR RESPONSES
- HIGH TEMPERATURE O2 SENSORS ALSO TESTED CONSISTENTLY PERFORMED WELL

WHITE SANDS TEST DATA

LT: Low Temperature Sensors

HT: High Temperature Sensors



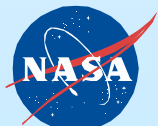
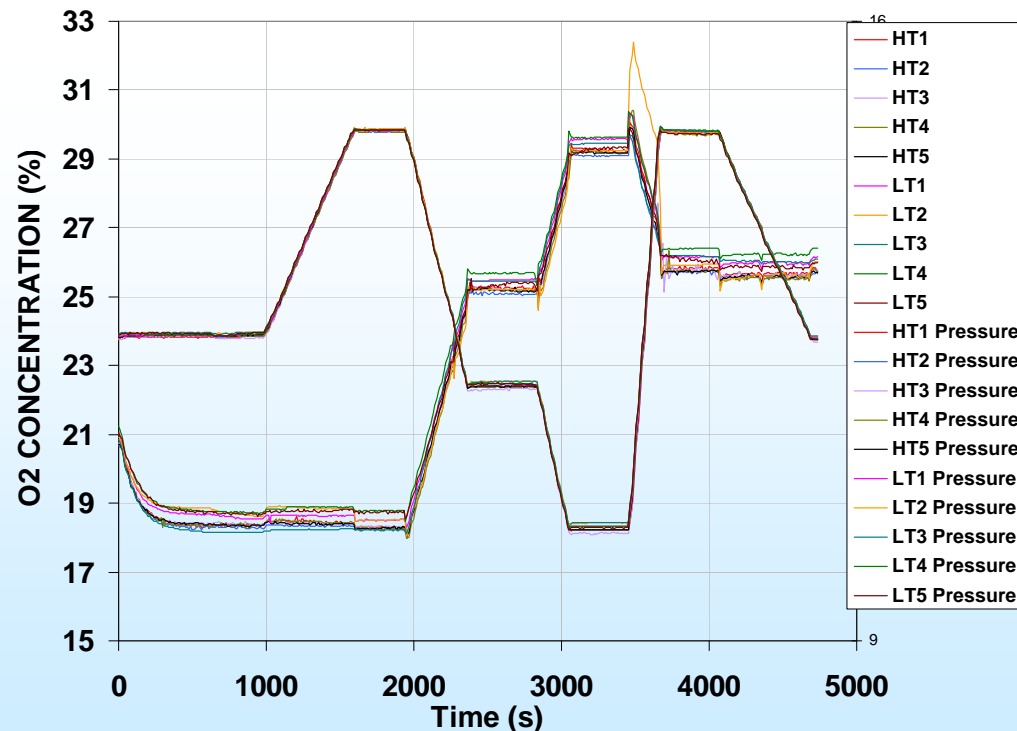
REPRESENTATIVE WHITE SANDS O2 TEST DATA (END OF TESTING)

- HIGH TEMPERATURE O2 SENSORS CONTINUED TO PERFORM WELL
- MAJOR ISSUES NEAR END OF TESTING FOR LOW TEMPERATURE SENSORS:
 - DRIFT IN SENSOR RESPONSE
 - NOISE IN SENSOR SIGNAL (CONNECTION ISSUES)
 - SPREAD OF SENSORS SIGNAL WITH TIME
- CONCLUSIONS
 - REPEATED TESTING OF LOW TEMPERATURE O2 SENSORS IN REPEATED CYCLES (INCLUDING PRESSURE CYCLES) REVEALED FAILURE MECHANISMS
 - HIGH TEMPERATURE O2 SENSORS VIABLE FOR FLIGHT NOW

WHITE SANDS TEST DATA (Pressure testing)

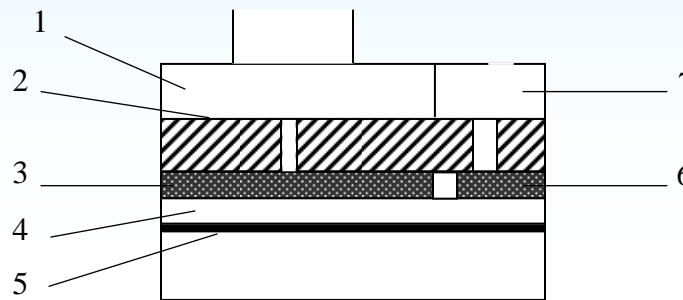
LT: Low Temperature Sensors

HT: High Temperature Sensors



POSSIBLE FAILURE MECHANISMS OF LOW TEMPERATURE SENSORS

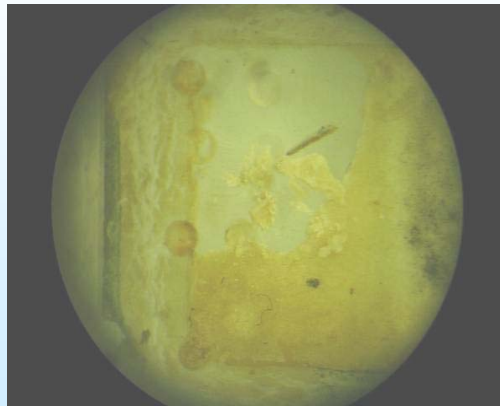
- **EXAMINE SENSOR STRUCTURES AFTER FAILURE**
 - **MULTIPLE COMPONENTS MAKE UP PRESENT SENSOR STRUCTURE**
 - **EROSION OF STRUCTURE OCCURS OVER TIME E.G. SEALS, DIFFUSION HOLES, ELECTRICAL CONNECTIONS**



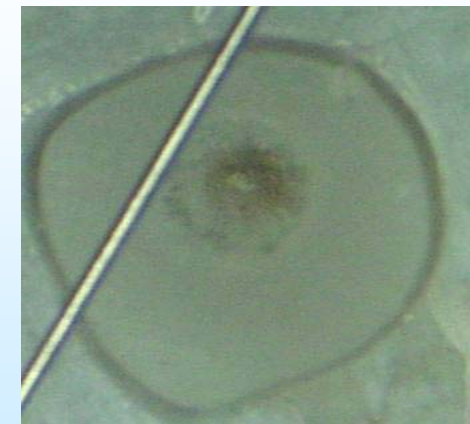
- 1. Sample gas chamber
- 2. capillary
- 3. working (sensing) electrode
- 4. SPE membrane
- 5. counter electrode
- 6. reference electrode
- 7. air cavity

Room Temperature O2 Sensor Structure

**Lower Seal
Breakdown and Filter
Paper Breakdown**

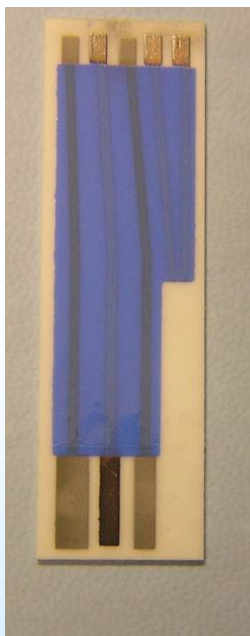


**Diffusion
Hole
Breakdown**

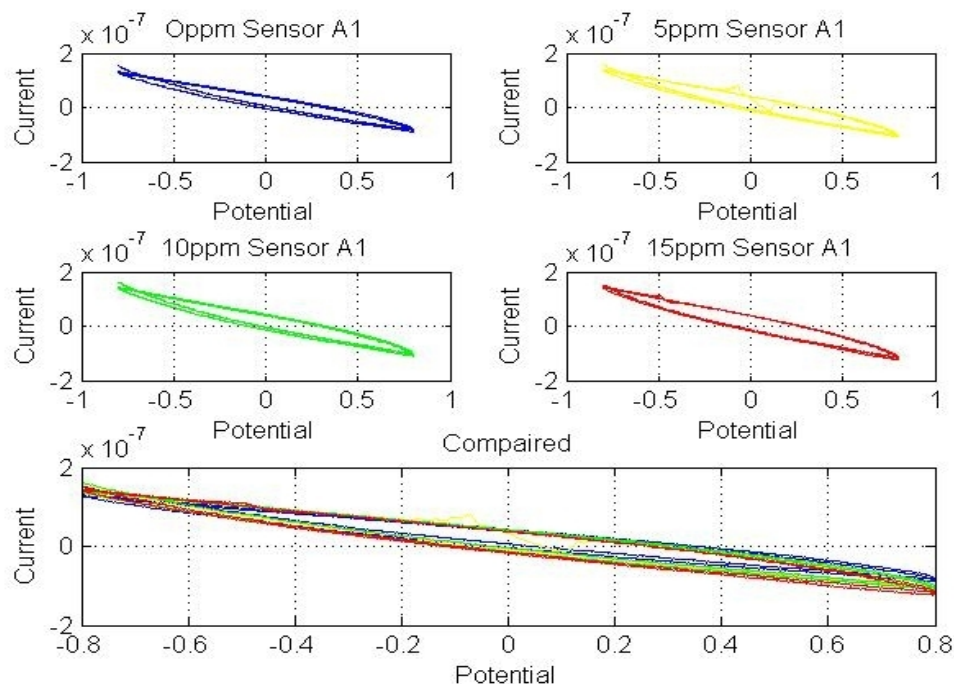


PRELIMINARY TESTING OF HCN/HCI SENSOR PLATFORM NAFION BASED ELECTROCHEMICAL CELL

- MODIFICATION OF ELECTRODES TO PRODUCE HCI OR HCN SENSITIVITY
- EARLY DESIGN TO TEST OUT BASIC SENSITIVITY
- PRELIMINARY TESTING FOR HCN RESPONSE
 - CYCLIC VOLTAMMETRY TO UNDERSTAND BASIC MECHANISM
 - SENSOR RESPONSE TO PPM LEVEL OF HCN
 - FURTHER OPTIMIZATION NECESSARY



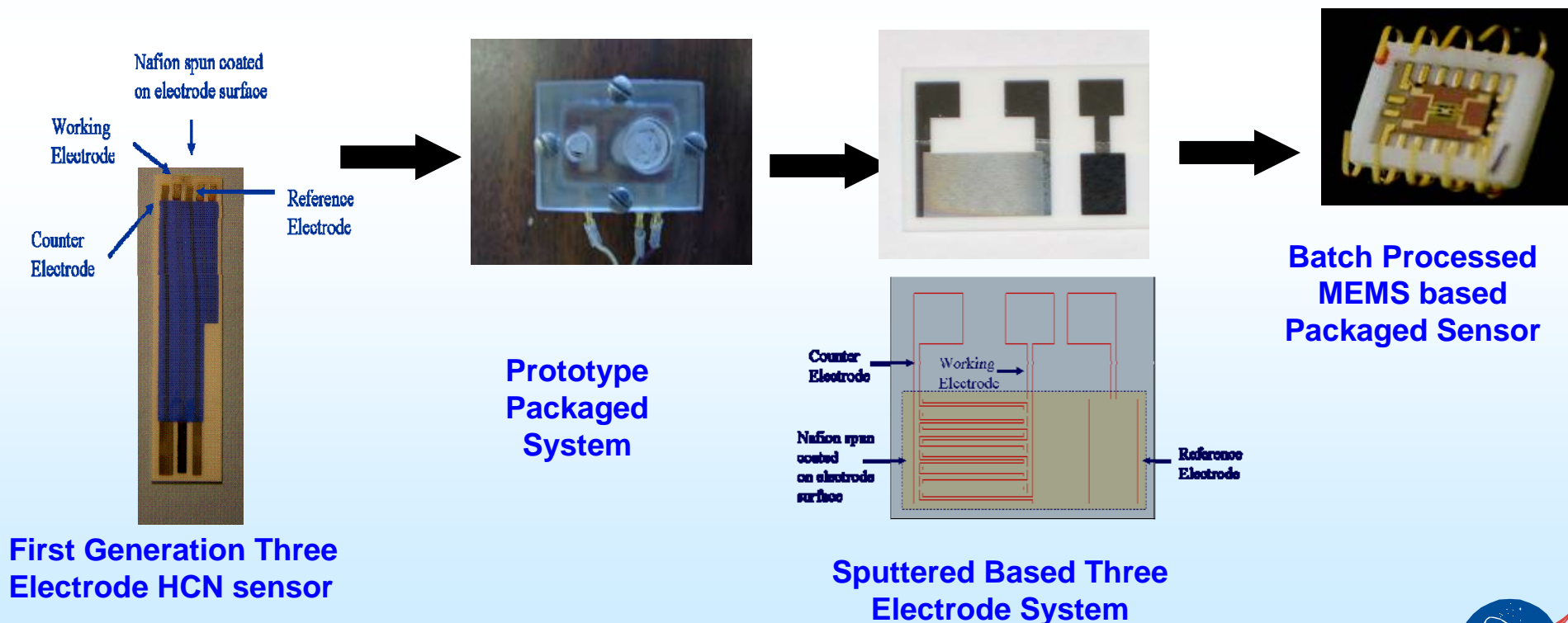
First Generation Three
Electrode HCN sensor



Preliminary Cyclic Voltammetry Response to Various
HCN Concentrations

POTENTIAL HCN/HCI SENSOR DEVELOPMENT APPROACH

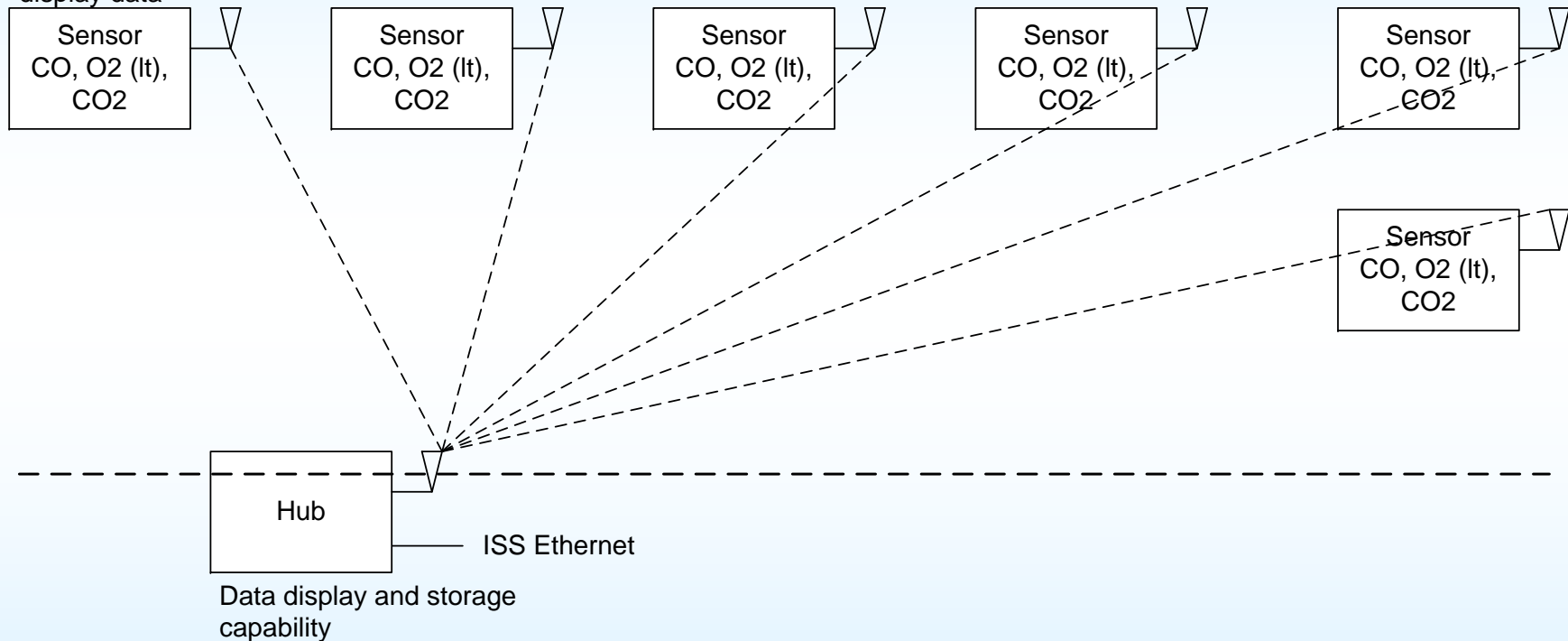
- INCREASE USE OF MICROFABRICATION TECHNOLOGY
 - NOT ONLY IN ELECTRODE FORMATION BUT ALSO COMPLETE SYSTEM PROCESSING
 - POTENTIAL TO ADDRESS PRESENT FAILURE MECHANISMS
 - REDUCED COSTS/BATCH PROCESSING
- EARLY STAGES OF IMPLEMENTATION OF SPUTTERING TECHNIQUES
- LONGER TERM: IMPLEMENTATION INTO “LICK AND STICK” WIRELESS PLATFORMS WITH MULTI-ELEMENT SENSOR SYSTEMS FORMING WIRELESS NETWORK



PROPOSED ARCHITECTURE WITH RF WIRELESS HUBS

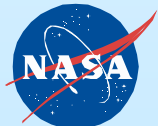
- FIRE AND ENVIRONMENTAL MONITORING RELEVANT
- BASIC SYSTEM DEMONSTRATED WITH O2 SENSORS
- APPROACH APPLICABLE TO MULTISENSOR SYSTEMS

Sensors do not store or display data



Pro:

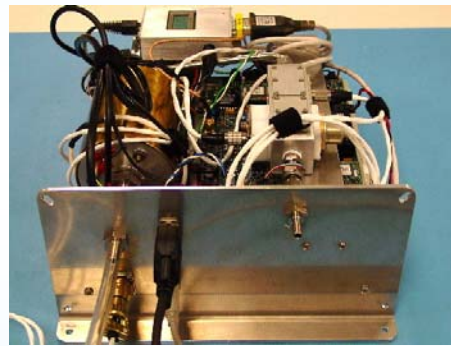
1. No computer resources required.
2. Ethernet connection to ISS
3. Ground or crew download of data from hub.
4. Data available from hubs in the event that the module is sealed off.



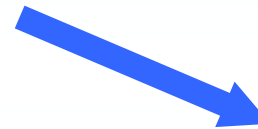
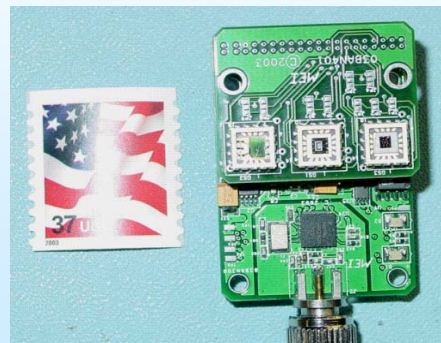
“LICK AND STICK” PLATFORM BEING TRANSITIONED FOR FIRE DETECTION APPLICATIONS

- **PROTOTYPE AIRCRAFT FIRE DETECTION SYSTEM: RANGE OF COMPONENTS TO ALLOW FIRE DETECTION WITH DECREASED FALSE ALARMS**
 - **COMPONENTS SUCH AS A PUMP INCLUDED**
- **LICK AND STICK HARDWARE COMPOSED OF PARTS SELECTED FOR FLIGHT APPLICATIONS**
- **FABRICATION OF FIRE DETECTION SYSTEM WITH “LICK AND STICK” HARDWARE APPROACH ON-GOING**

Prototype Aircraft Cargo Bay Fire Detection System with chemical sensors, particulate detector, pump, and control hardware



“Lick and Stick” Sensor Platform Used Leak Detection Applications with sensors, power, communication, control hardware all in a miniaturized package

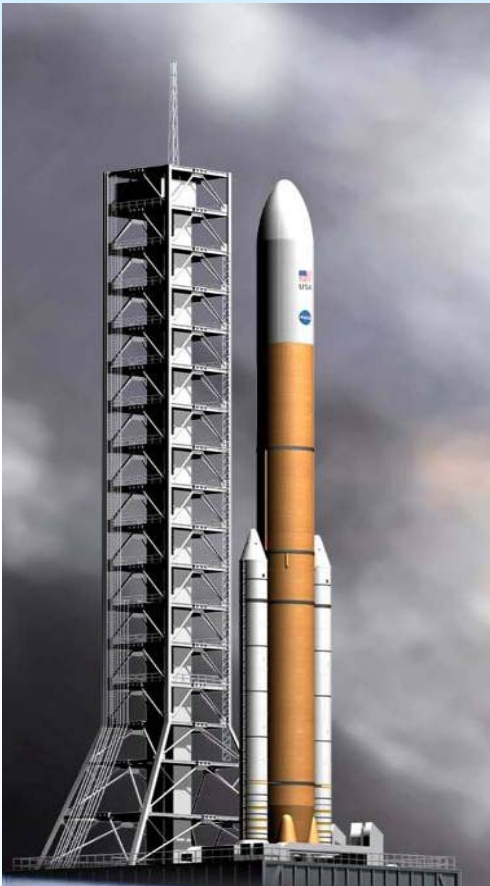


Four Channel Fire Detection System Using “Lick and Stick” Electronics Hardware

LICK AND STICK SYSTEMS

BRIEF LIST OF LAUNCH, IN-SPACE, AND LUNAR APPLICATIONS

LAUNCH



Propellant Leaks
Toxic Gas Leaks
Environmental Monitoring
Fire Detection

IN-SPACE

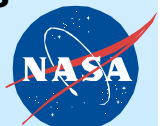


Propellant Fuel Leaks
Toxic Gas Leaks
Environmental Monitoring
Fire Detection
EVA

LUNAR



Propellant Fuel Leaks
Toxic Gas Leaks
Environmental Monitoring
Fire Detection
EVA
ISRU Applications



SUMMARY

- **AEROSPACE APPLICATIONS REQUIRE A RANGE OF CHEMICAL SENSING TECHNOLOGIES**
- **FIRE DETECTION AND ENVIRONMENTAL MONITORING NEEDS CAN BE ADDRESSED BY SOLID STATE SENSORS AND “LICK AND STICK” SENSOR SYSTEM SYSTEMS**
- **TRANSITION OF HIGH TEMPERATURE BASE PLATFORMS TO LOWER TEMPERATURE SYSTEMS ON-GOING**
- **NAFION ELECTROCHEMICAL CELL PLATFORM DEVELOPMENT**
 - **APPLICABLE TO O₂, HCN, HCl AND OTHER SPECIES**
 - **O₂ SENSOR MOSTLY DEVELOPED BUT REQUIRES REFINEMENT.**
- **EXTENSIVE CHARACTERIZATION OF BOTH NAFION O₂ SENSORS AND HIGH TEMP O₂ SENSORS ON-GOING FOR POSSIBLE ISS AND CEV APPLICATION**
 - **DETERMINE MATURITY FOR POSSIBLE IMPLEMENTATION**
 - **DETERMINE SENSOR LIFE AND FAILURE MECHANISMS**
- **HIGH TEMP O₂ SENSORS VIABLE FOR APPLICATION AT THIS TIME**
- **ROOM TEMP NAFION SENSORS REQUIRE FURTHER MATURATION/FAILURE MECHANISMS IDENTIFIED**
- **LONG TERM APPROACH:**
 - **INCREASED USE OF MICROFABRICATON TECHNOLOGY WHERE APPROPRIATE FOR NAFION PLATFORM**
 - **MULIPARAMETER SENSOR SYSTEM USING “LICK AND STICK” TECHNOLOGY**

