Cutting Edge Technologies Presentation: An Overview of Developing Sensor Technology Directions and Possible Barriers to New Technology Implementation

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The aerospace industry requires the development of a range of chemical sensor technologies for such applications as leak detection, emission monitoring, fuel leak detection, environmental monitoring, and fire detection. A range of chemical sensors are being developed based on micromachining and microfabrication technology to fabricate microsensors with minimal size, weight, and power consumption; and the use of nanomaterials and structures to develop sensors with improved stability combined with higher sensitivity, However, individual sensors are limited in the amount of information that they can provide in environments that contain multiple chemical species. Thus, sensor arrays are being developed to address detection needs in such multi-species environments. These technologies and technical approaches have direct relevance to breath monitoring for clinical applications. This presentation gives an overview of developing cutting-edge sensor technology and possible barriers to new technology implementation. This includes lessons learned from previous microsensor development, recent work in development of a breath monitoring system, and future directions in the implementation of cutting edge sensor technology.

Cutting Edge Technologies Presentation:

An Overview of Developing Sensor Technology Directions and Possible Barriers to New Technology Implementation

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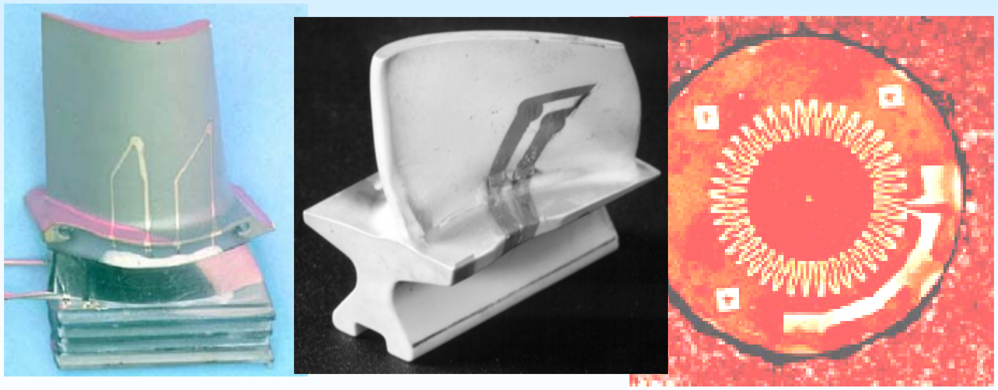
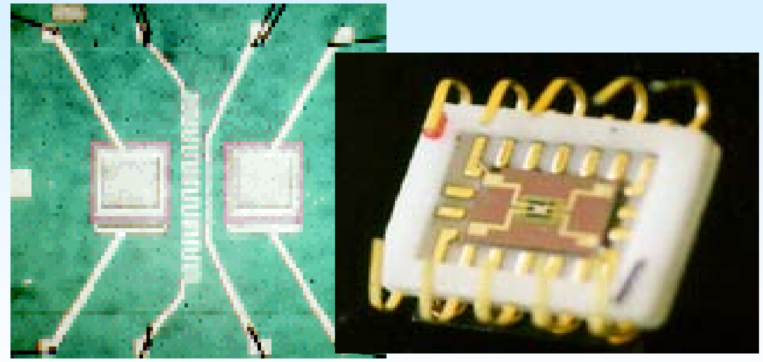
SENSORS AND ELECTRONICS BRANCH

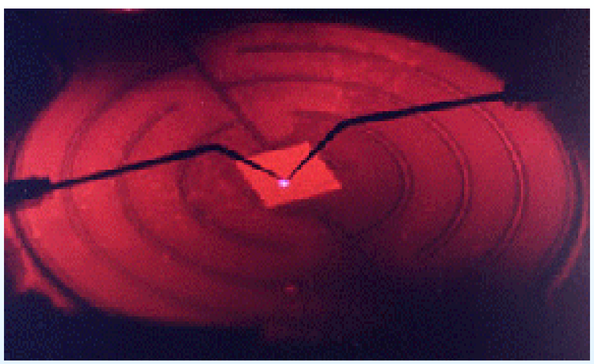
SCOPE OF WORK



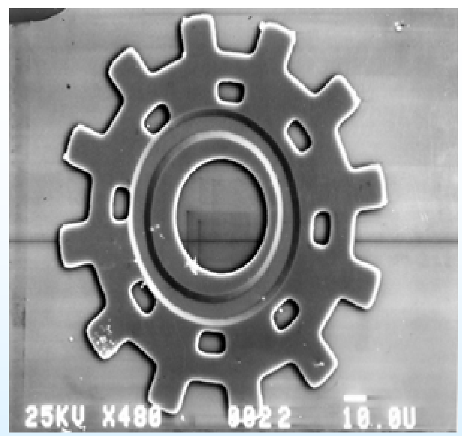
PHYSICAL SENSORS (T, Strain, Heat Flux)



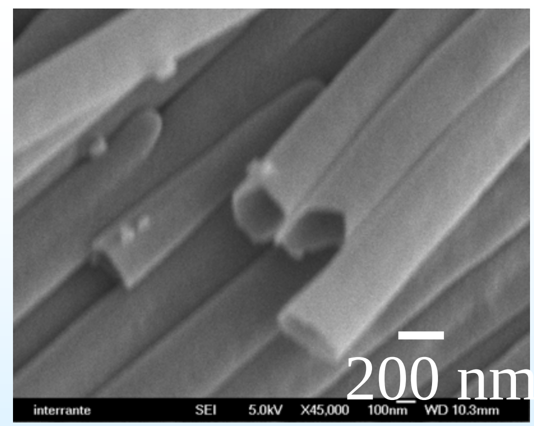
CHEMICAL SENSORS



SILICON CARBIDE HIGH TEMP ELECTRONICS



MICRO-ELECTRO-MECHANICAL SYSTEMS



NANOTECHNOLOGY

MICROFABRICATED GAS SENSORS

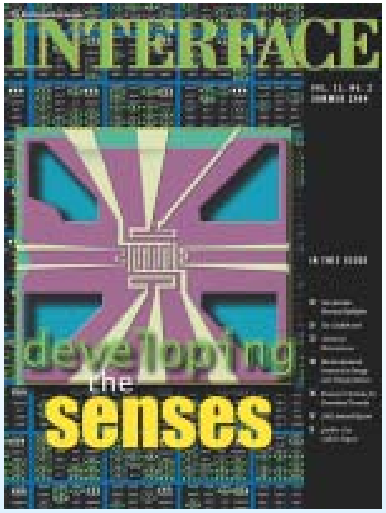
- COLLABORATIVE EFFORT BETWEEN NASA GRC, CASE WESTERN RESERVE, and OHIO STATE UNIVERSITY

- SENSOR DEVELOPMENT RESULTING FROM:
  - IMPROVEMENTS IN MICROFABRICATION AND MICROMACHINING TECHNOLOGY
  - NANOMATERIALS
  - DEVELOPMENT OF SiC-BASED SEMICONDUCTOR TECHNOLOGY

- GAS DETECTION IN:
  - HARSH ENVIRONMENTS
  - APPLICATIONS BEYOND CAPABILITIES OF COMMERCIAL SENSORS

- PLATFORMS TECHNOLOGY DEVELOPED FOR A VARIETY OF MEASUREMENTS
  - SCHOTTKY DIODE
  - RESISTANCE BASED
  - ELECTROCHEMICAL

- TARGET DETECTION OF GASES OF FUNDAMENTAL INTEREST
  - HYDROGEN (H_2)
  - HYDROCARBONS (C_xH_y)
  - NITROGEN OXIDES (NO_X) AND CARBON MONOXIDE (CO)
  - OXYGEN (O_2)
  - CARBON DIOXIDE (CO_2)
  - HYDRAZINE



NASA GRC/CWRU O2 Sensor Featured On the Cover of the Electrochemical Society Interface Magazine

BASE PLATFORM SENSOR TECHNOLOGY

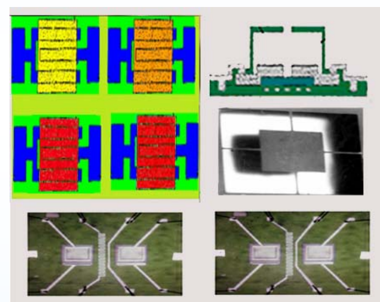
Integration of Micro Sensor Combinations into Small, Rugged Sensor Suites

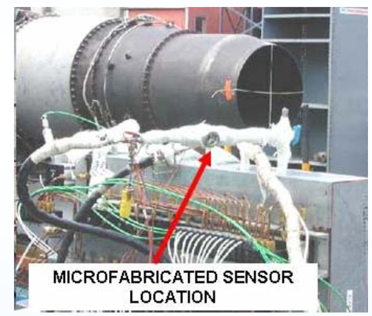
Example Applications: AEROSPACE VEHICLE FIRE, FUEL LEAKS, EMISSIONS, ENVIRONMENTAL MONITORING CREW HEALTH, SECURITY

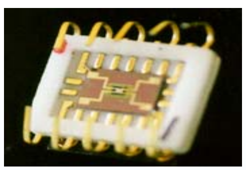
Multi Species Fire Sensors for Aircraft Cargo Bays

"Lick and Stick" Space Launch Vehicle Leak Sensors with Power and Telemetry

Aircraft Propulsion Exhaust High Temperature Electronic Nose

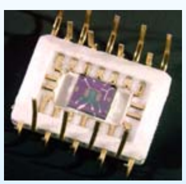




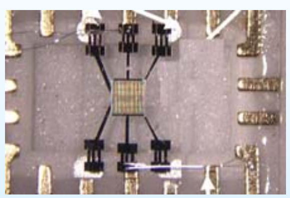


Oxygen Sensor

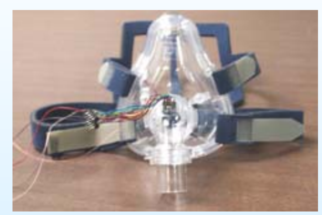
SiC Hydrocarbon Sensor



H2 Sensor



Nanocrystalline Tin Oxide NOx and CO Sensor



Sensor Equipped Prototype Medical Pulmonary Monitor

Hydrazine EVA Sensors (11 ppb Detection)

CWRU

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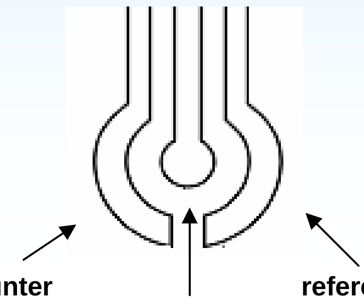
NASA

BASE PLATFORM SENSOR TECHNOLOGY

- SENSOR DEVELOPMENT RESULTING FROM:
  - MICROFABRICATION AND MICROMACHINING TECHNOLOGY
  - NANOMATERIALS
  - SiC-BASED SEMICONDUCTOR TECHNOLOGY
- TECHNOLOGY DEVELOPS PLATFORMS FOR A VARIETY OF MEASUREMENTS
  - SCHOTTKY DIODE
  - RESISTANCE BASED
  - ELECTROCHEMICAL
- MODIFY PLATFORMS AND MATERIALS TO MEET NEEDS OF THE APPLICATION

BASIC APPROACH



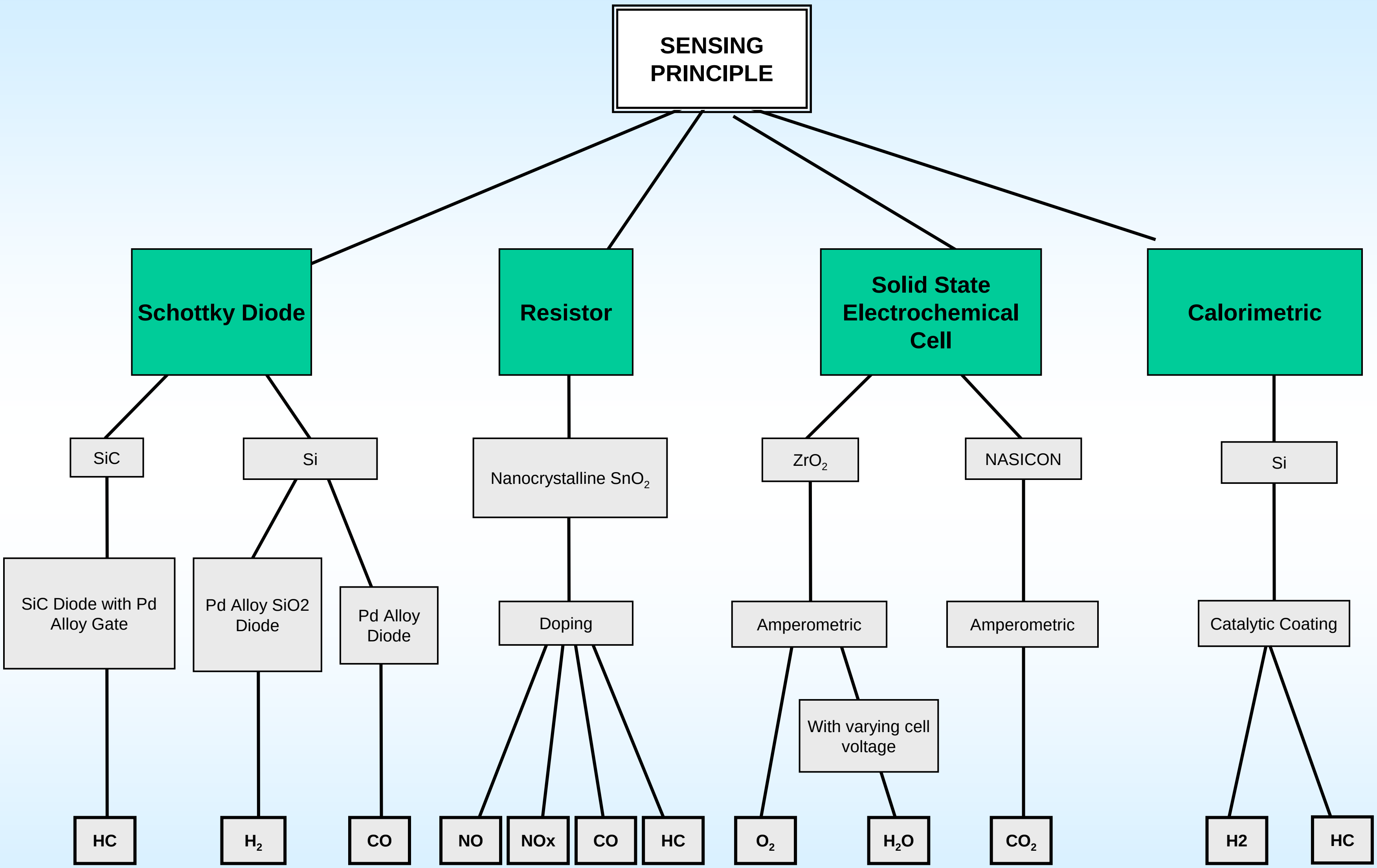
Electrochemical Cell Platform formed by Microprocessing

Vary Substrate and Sensor Materials Depending on Application

High Temp O2 Detection	High Temp CO2 Detection	Room Temp O2 Detection	Glucose sensor	Ca++ Detection

Meet the Needs of a Range of Applications Based On Platform Technology

CHEMICAL SENSOR “FAMILY TREE”



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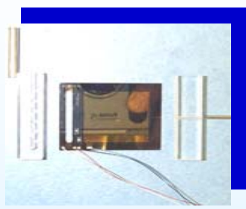
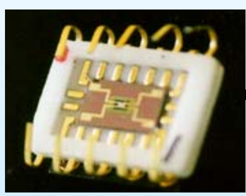
One Potential EVA Vision: “Smart” Suit

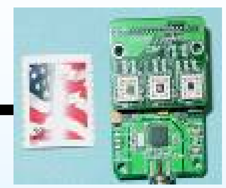
- **Development of a “Smart” Suit which has self-monitoring, caution and warning, and control capabilities with high levels of reliability, durability, and safety.**
- **Small, lightweight, low power sensor systems, with increased packaging flexibility, will improve the effectiveness and extensibility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

Micro Particulate Classifier

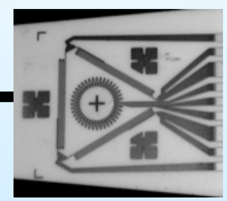


Micro Chemical Sensor





“Lick and Stick” Self Contained MicroSensor System



Multifunctional Physical Sensor

A “SMART” SUIT NEEDS TO MONITOR BOTH INTERNAL AND EXTERNAL CONDITIONS

POSSIBLE STEPS TO REACH INTELLIGENT SYSTEMS

- **"LICK AND STICK" TECHNOLOGY (EASE OF APPLICATION)**
  - **Micro and nano fabrication to enable multipoint inclusion of sensors, actuators, electronics, and communication throughout the vehicle without significantly increasing size, weight, and power consumption. Multifunctional, adaptable technology included.**
- **RELIABILITY:**
  - **Users must be able to believe the data reported by these systems and have trust in the ability of the system to respond to changing situations e.g. decreasing sensors should be viewed as decreasing the available information flow about a vehicle. Inclusion of intelligence more likely to occur if it can be trusted.**
- **REDUNDANCY AND CROSS-CORRELATION:**
  - **If the systems are easy to install, reliable, and do not increase weight/complexity, the application of a large number of them is not problematic allowing redundant systems, e.g. sensors, spread throughout the vehicle. These systems will give full-field coverage of the engine parameters but also allow cross-correlation between the systems to improve reliability of sensor data and the vehicle system information.**
- **ORTHOGONALITY:**
  - **Systems should each provide a different piece of information on the vehicle system. Thus, the mixture of different techniques to "see, feel, smell, hear" as well as move can combine to give complete information on the vehicle system as well as the capability to respond to the environment.**

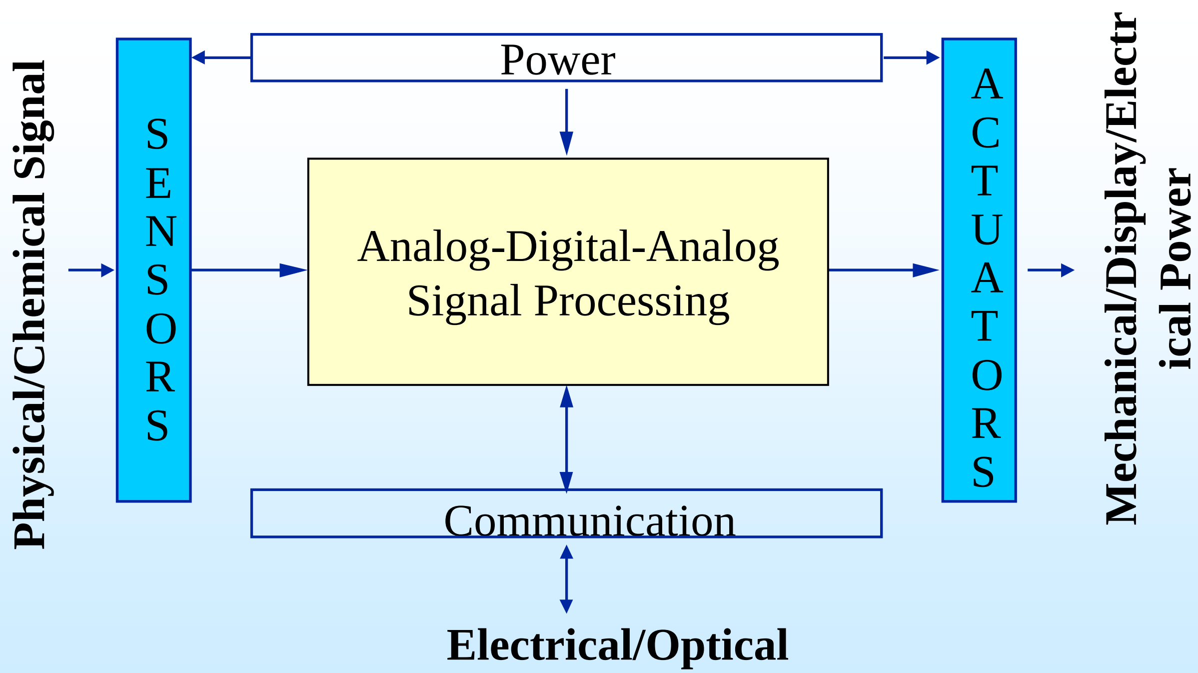
SENSOR AND INSTRUMENTATION DEVELOPMENT

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

CUTTING EDGE TECHNOLOGY

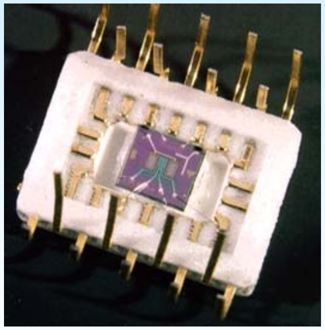
- THIS PRESENTATION DISCUSSES A RANGE OF GAS SENSOR TECHNOLOGY
- ILLUSTRATING BOTH THE SENSOR TECHNOLOGY TRENDS AND LESSONS LEARNED
- EXAMPLES REVOLVE AROUND MICROSYSTEMS TECHNOLOGY
- DISCUSS THE VIABILITY OF NANOTECHNOLOGY
- EXAMPLES REVOLVE AROUND AEROSPACE APPLICATIONS BUT HAVE BROADER IMPLICATIONS
- IMPLEMENTATION IN BIOMEDICAL APPLICATIONS
- FUTURE DIRECTIONS

Microsystem Block Diagram



MINIATURIZED SYSTEM
TAILORED FOR THE APPLICATION

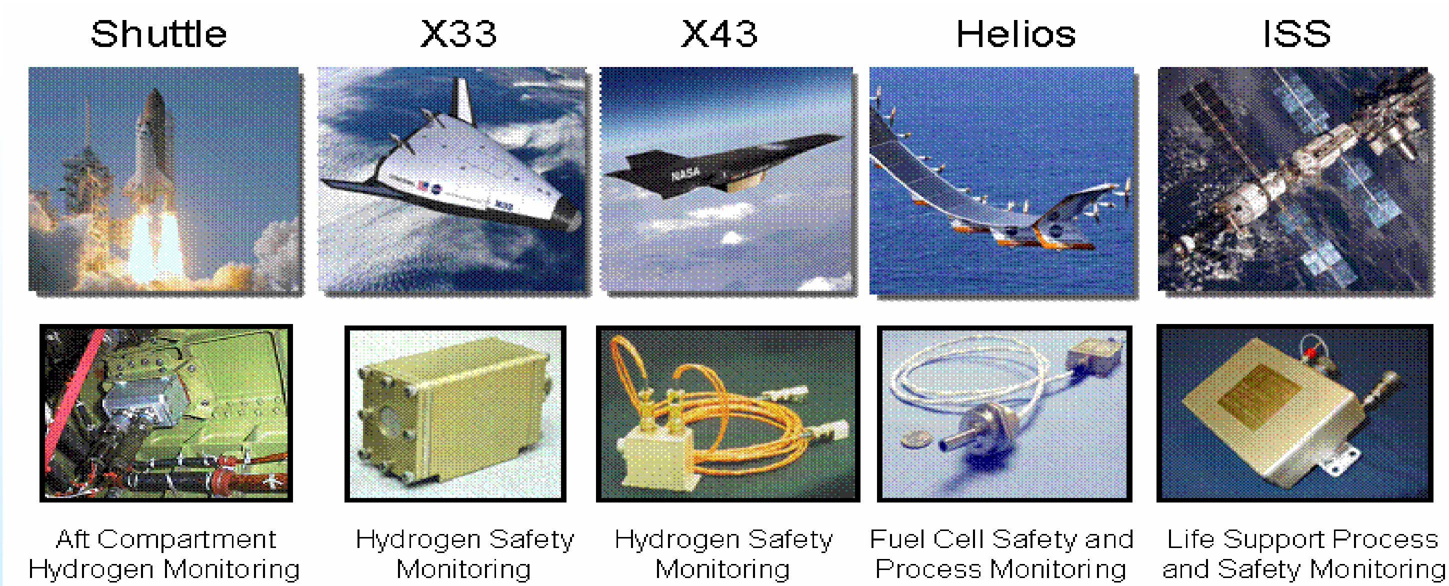
HYDROGEN LEAK SENSOR TECHNOLOGY



- *MASS SPECTROMETER CANNOT BE USED IN-FLIGHT; SENSOR SYSTEM TO PROVIDE NEEDED FUNCTIONALITY*
- MICROFABRICATED USING MEMS-BASED TECHNOLOGY FOR MINIMAL SIZE, WEIGHT AND POWER CONSUMPTION
- HIGHLY SENSITIVE IN INERT OR OXYGEN-BEARING ENVIRONMENTS, WIDE CONCENTRATION RANGE DETECTION

1995 R&D 100 AWARD WINNER

NASA 2003 TURNING GOALS INTO REALITY SAFETY AWARD



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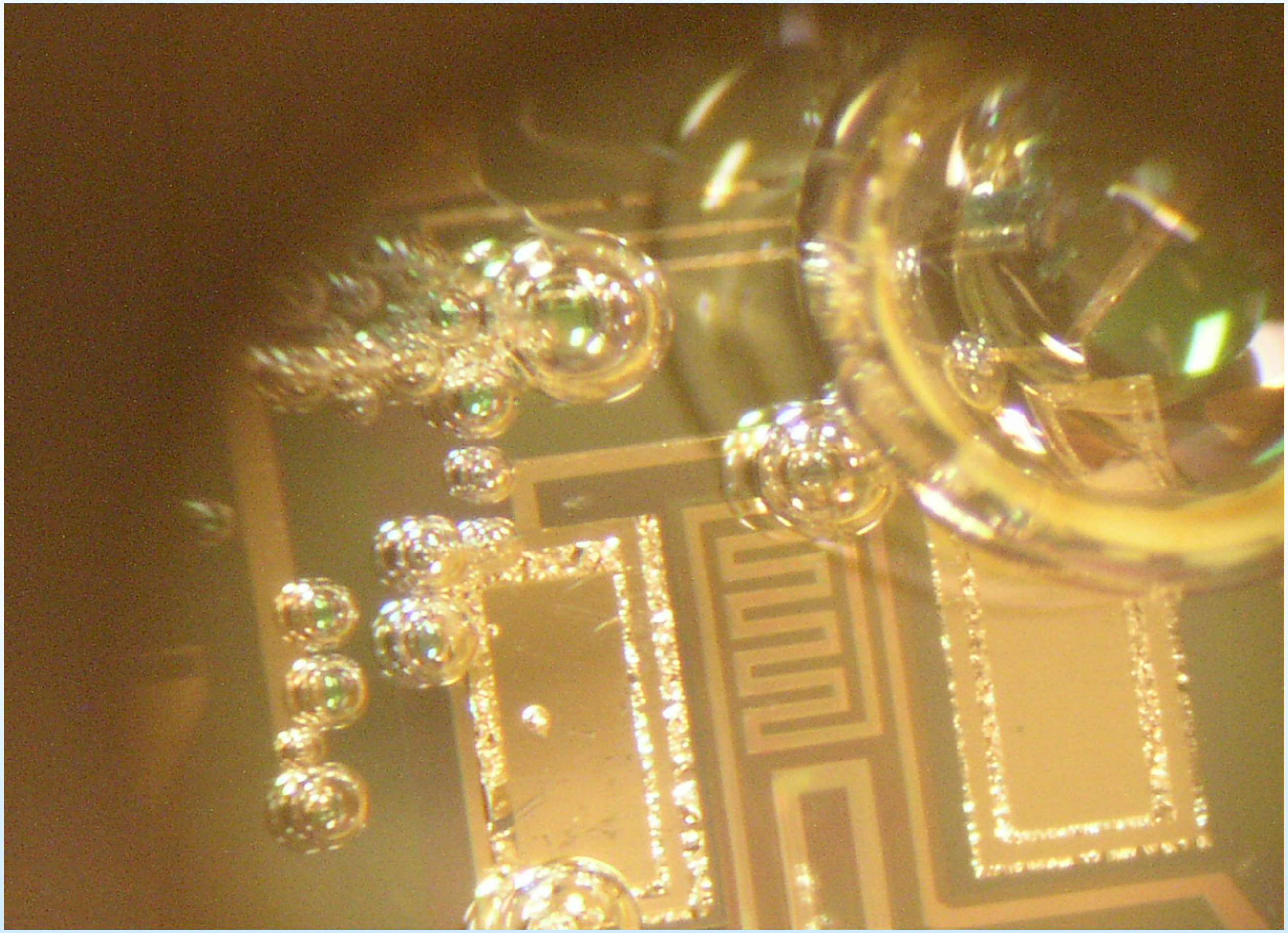
TAILOR THE SENSOR FOR THE APPLICATION

H2 SENSOR WORKS IN A WIDE VARIETY OF APPLICATIONS BUT CANNOT WORK IN EVERY ENVIRONMENT

RIGHT SENSOR FOR RIGHT APPLICATION

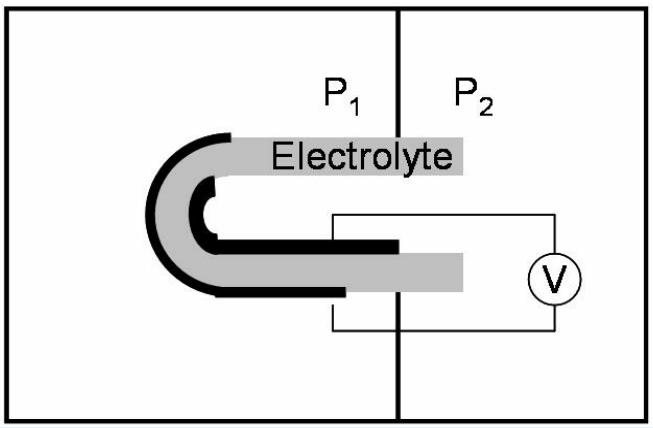
H2 SENSOR OPERATION UNDER WATER



INCREASED MINIATURIZATION
MICROFABRICATION IS NOT JUST MAKING SOMETHING SMALLER

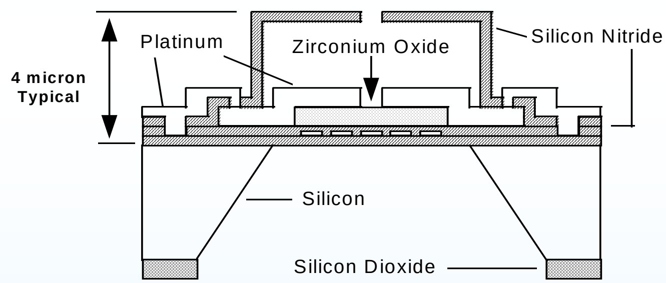
MICROFABRICATED OXYGEN SENSOR TECHNOLOGY

- **OXYGEN SENSORS HAVE BEEN IN CARS FOR YEARS; SIGNIFICANT POWER CONSUMPTION (ORDER OF WATTS)**
- **SIGNIFICANT ACTIVITY IN DEVELOPING A MICROFABRICATED AND MICROMACHINED SENSOR FOR MINIMAL SIZE, WEIGHT AND POWER CONSUMPTION (ON THE ORDER OF HUNDREDS OF MILLIWATTS)**
- **HOWEVER, THE SIZE OF THE STRUCTURE COMBINED WITH THE OPERATING TEMPERATURE HAVE LED TO THEIR OWN CHALLENGES IN DEVICE FABRICATION**

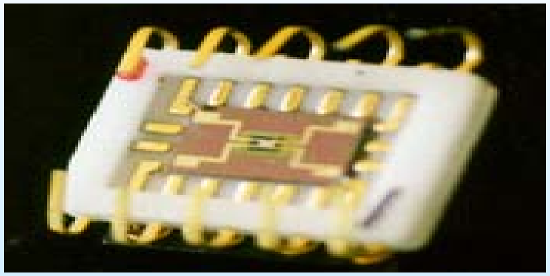


Heated Exhaust Gas Oxygen (HEGO) or Lambda Sensor

$$E = (RT/nF)\ln(P_1/P_2)$$



Not to scale:

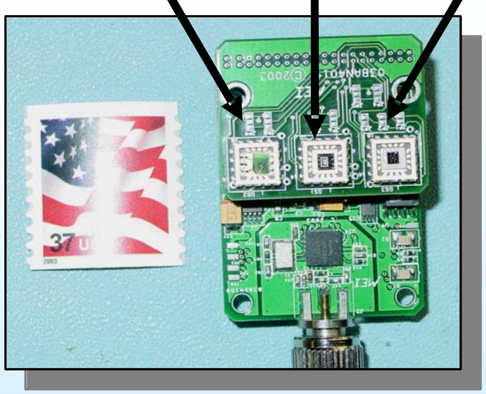


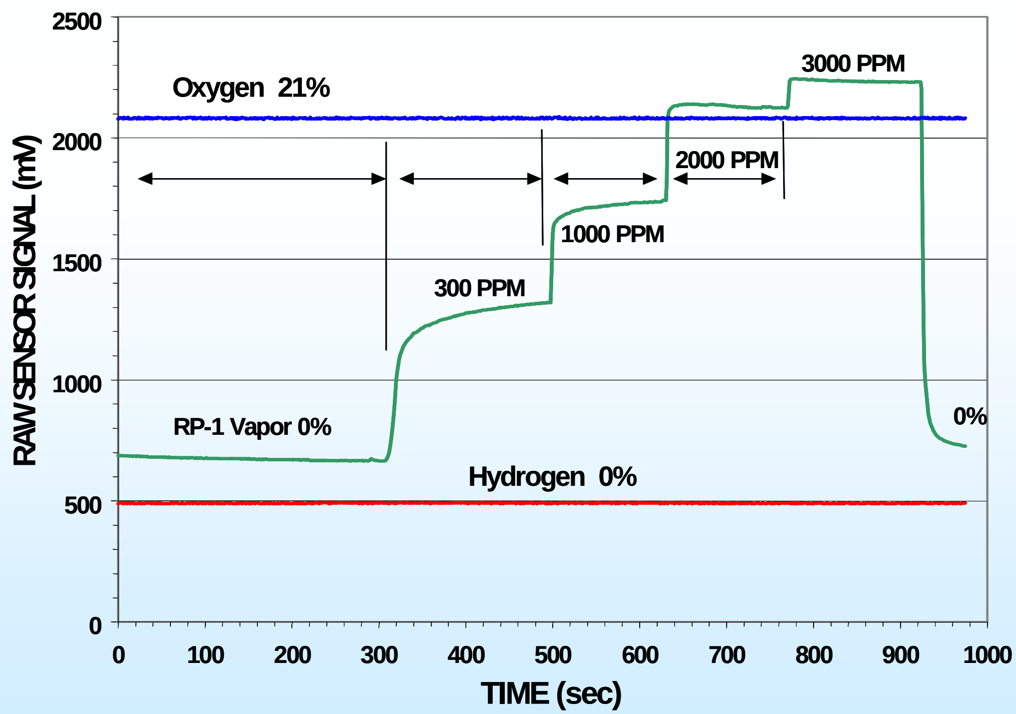
ZrO2 Oxygen Sensor

COMPLETE STAND-ALONE SMART SENSOR SYSTEM
MULTICOMPONENT SENSOR ARRAY
SUPPORTING TECHNOLOGIES ALLOW POSSIBLE IMPLEMENTATION

"LICK AND STICK" LEAK SENSOR SYSTEM

- THREE SENSORS, SIGNAL CONDITIONING, POWER, AND TELEMETRY ALL IN SINGLE PACKAGE
- H2, O2, AND HYDROCARBON SENSORS ALLOW DETECTION OF BOTH FUEL AND OXYGEN
- BUILT IN TEST OF ELECTRONICS AND SENSOR
- BEING MATURED FOR CREW LAUNCH VEHICLE AVIONICS





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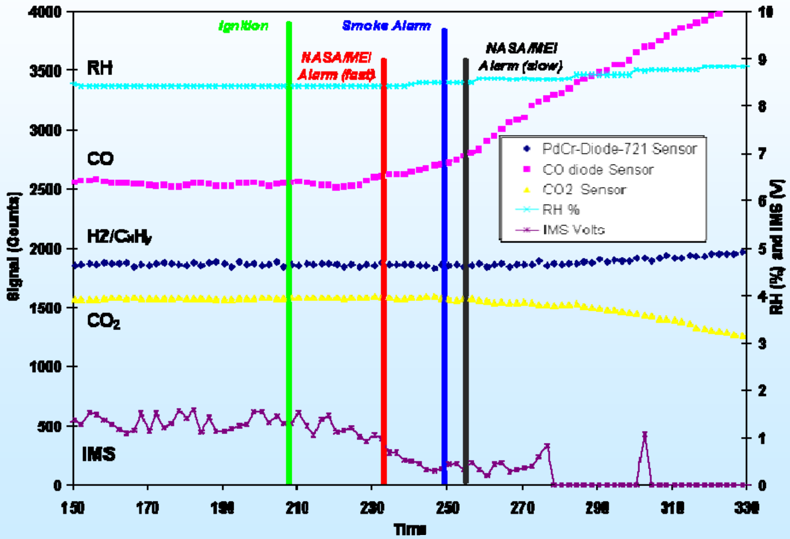
SENSOR ARRAY
MULTIPARAMETER/ORTHOGONALITY

MICRO-FABRICATED GAS SENSORS FOR LOW FALSE ALARMS

2005 R&D 100 AWARD WINNER

NASA 2005 TURNING GOALS INTO REALITY AA CHOICE

- **SIGNIFICANT FALSE ALARM RATE FOR FIRE DETECTORS IN CARGO BAY OF AIRCRAFT AS HIGH AT 200:1**
- **COMBINE BOTH PARTICULATE AND CHEMICAL SENSORS TO IMPROVE SENSOR SYSTEM RELIABILITY**
  - **CO AND CO2 SENSORS CENTRAL TO APPROACH**
  - **MINIATURIZATION OF PARTICULATE SENSOR**
- **FAA CARGO BAY FIRE TESTING**
  - **NO FALSE ALARMS**
  - **CONSISTENT DETECTION OF FIRES**

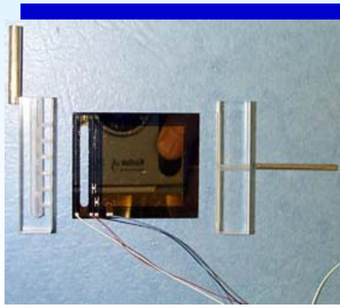


MINIATURIZED SYSTEM
TAILORED FOR THE APPLICATION

DUST MONITORING

1

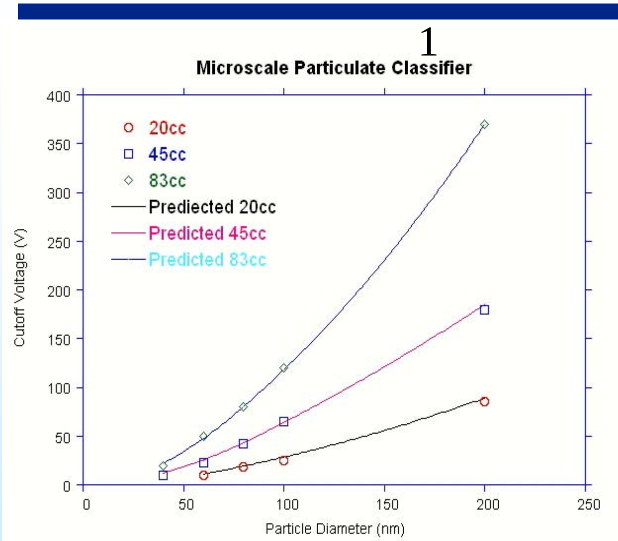
Low cost sensor fabricated using wafer processing techniques



2

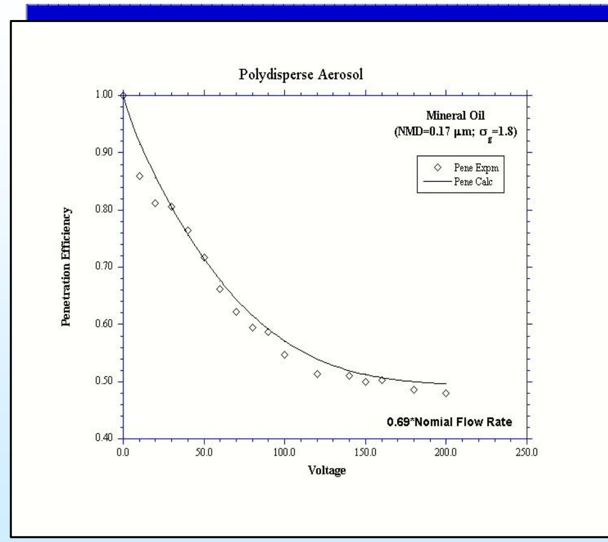
Completed sensor contrast with traditional macroscale classifier.

2



Good agreement between predicted and observed performance.

4



Correct retrieval of size distribution of test aerosol.

NANOTECHNOLOGY DEVELOPMENT

NANO DIMENSIONAL CONTROL PREVALENT IN CHEM/BIO SENSORS

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

SAME

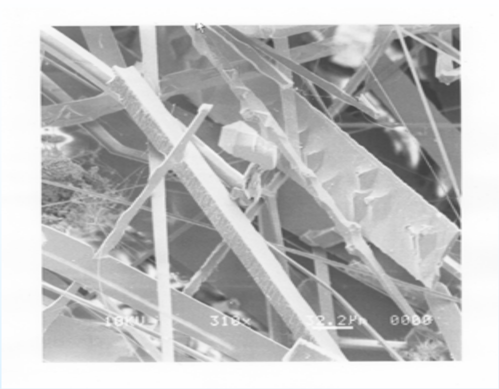
- APPLICATIONS DON'T CARE THAT IT IS NANO, NEED IMPROVED CAPABILITIES
- STANDARD SENSOR TECHNOLOGY REQUIREMENTS, POTENTIAL, AND DIRECTIONS SET BY THE ADVENT OF MICROTECHNOLOGY REMAIN CONSTANT
- SENSITIVITY, SELECTIVITY, STABILITY, RESPONSE TIME, TAILOR FOR THE APPLICATION, "LICK AND STICK", ETC.
- PACKAGING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

TARGETED TECHNOLOGY DEVELOPMENT

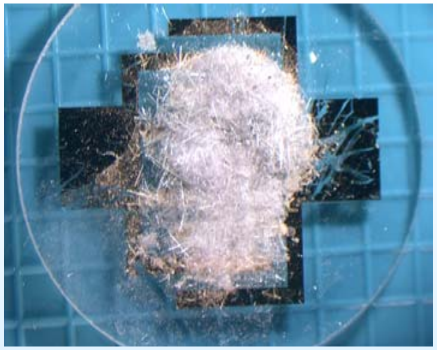
- MICRO-NANO CONTACT FORMATION
- NANOMATERIAL STRUCTURE CONTROL
- OTHER NANO OXIDE MATERIALS

MICRO-NANO CONTACT FORMATION

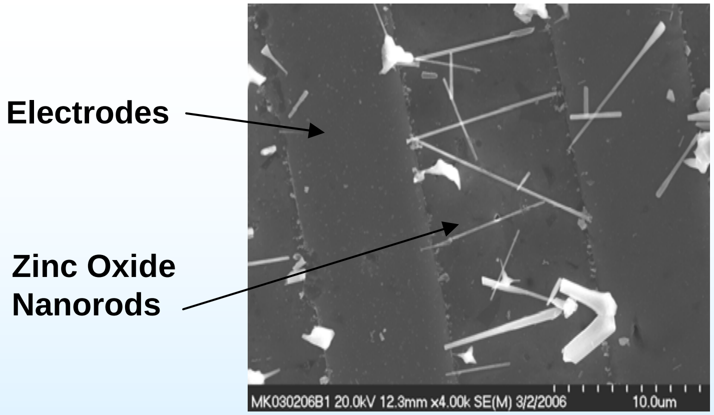
- NO MATTER HOW GOOD THE SENSOR, IF YOU CANNOT MAKE CONTACT WITH IT, THEN IT WILL NOT BE INEFFECTIVE
- MICRO-NANO INTEGRATION/CONTACTS
  - MAJOR QUESTION FOR NANOSTRUCTURED BASED SENSORS: HOW ARE THE NANOSTRUCTURED MATERIALS INTEGRATED INTO A MICRO/MACRO STRUCTURE
- MANUAL METHODS GENERALLY INVOLVE REPEATABILITY ISSUES E.G.
  - DENSITY OF THE NANOROD MATERIALS,
  - QUALITY OF THE CONTACT
  - VARIATION OF BASELINE MATERIAL PROPERTIES
- BASIC WORK ON-GOING TO IMPROVE MICRO-NANO CONTACTS E.G. USE OF DIELECTROPHORESIS TO ALIGN NANOSTRUCTURES



NANOSTRUCTURE FABRICATED BY THERMAL EVAPORATION-CONDENSATION PROCESS.



NANORODS CONTACTED WITH THE SUBSTRATE VIA A SILVER EPOXY



ZINC OXIDE NANORODS AFTER DIELECTROPHORESIS ACROSS INTERDIGITATED FINGERS

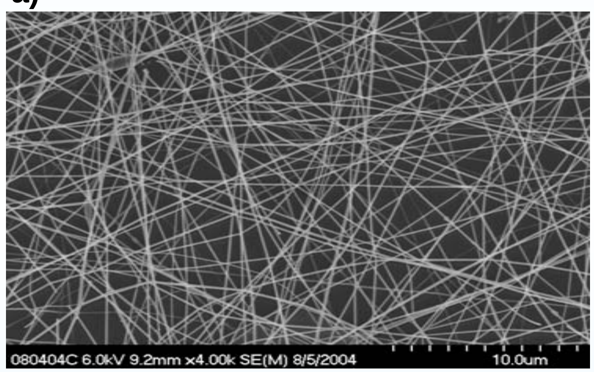
NANOMATERIAL STRUCTURE CONTROL

- DIFFERENT PROCESSING TECHNIQUES RESULT IN VERY DIFFERENT CRYSTAL STRUCTURES.
  - APPROACH: CONTROL NANOSTRUCTURE CRYSTAL STRUCTURE FORMATION TO CONTROL SENSOR RESPONSE
  - SNO2: SENSOR RESPONSE IS GRAIN DEPENDENT FOR MICRO/NANO GRAINED MATERIAL
  - SENSING MECHANISM FOR NANOSTRUCTURES STILL BEING EXPLORED

Electrospinning | TEC Condensation

SEM

a)



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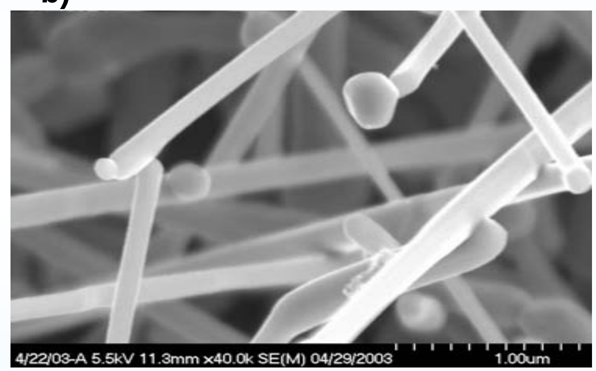
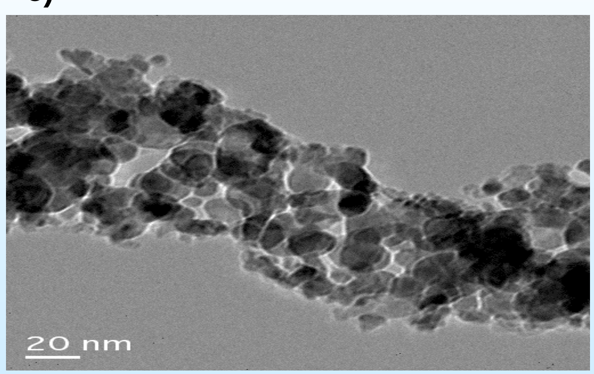


HRTEM

c)



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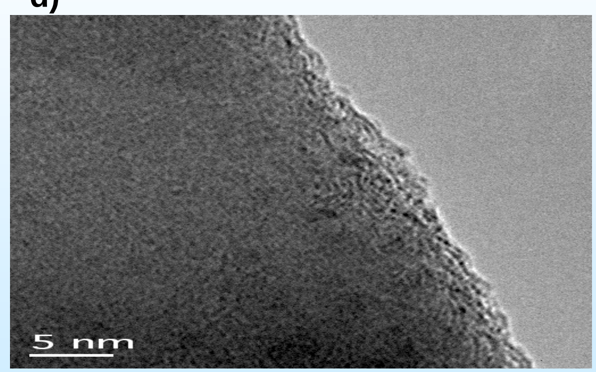
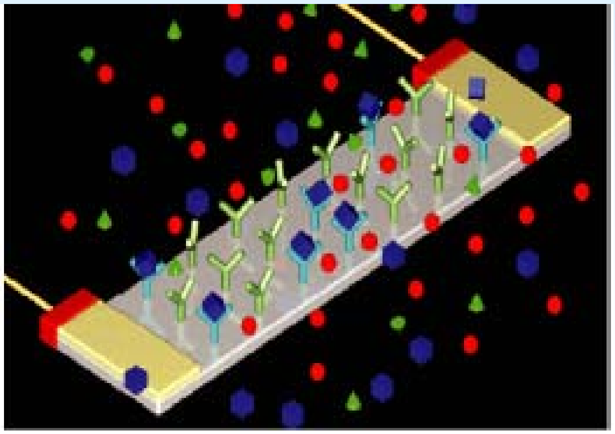


"LOCK AND KEY" CHEMICAL SENSORS USING NANOSTRUCTURES

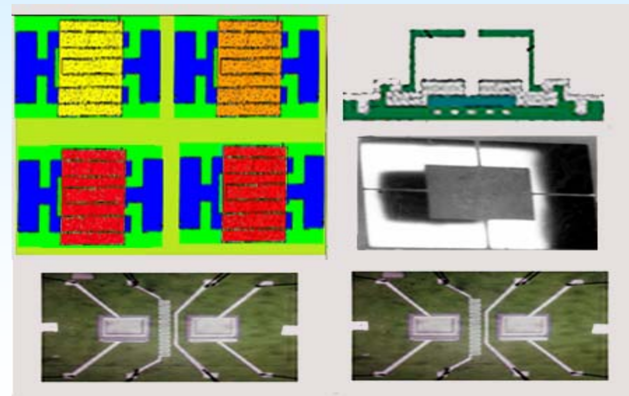
- **OBJECTIVE: DEMONSTRATE THE FUNDAMENTAL ABILITY TO ASSEMBLE THE ULTIMATE "LOCK AND KEY" CHEMICAL SENSOR DETECTION SYSTEM**
- **STATE OF THE ART:**



Limited Chemical Selectivity by use "Lock and Key" Approach

Many Species, Complex Structures Lead to Limited Ability For Species Identification

NASA GRC HIGH TEMP NOSE APPROACH



Nose Approaches necessary to attempt to understand environment but still limited in species identification: multispecies identification, closely related species, significant false positives

- **TECHNICALLY ADDRESS THE FUNDAMENTAL QUESTION "WHAT IS NANO GOOD FOR?" IN THE AREA OF CHEMICAL SENSORS:**
  - ➢ ***NOT*** **SMALL NANO STRUCTURES FOR BILLION MOLECULE MEASUREMENTS/ IN SUCH APPLICATIONS MAY CONSIDER THIN FILMS OR ALTERNATE SENSOR PLATFORMS**
  - ➢ ***INSTEAD*** **USE NANOSTRUCTURES FOR DETECTION ON MOLECULAR LEVEL**
- **ARRANGE THE CHEMICAL SENSOR STRUCTURE TO "FIT" THE MOLECULE IN QUESTION**
- **VERIFY THE PRESENCE OF THE MOLECULE WITH AN ELECTROCHEMICAL SIGNATURE**
- **FABRICATE "DESIGNER" CHEMICAL SENSORS**

RELEVANCE TO BIOMEDICAL STUDIES AND CLINICAL APPLICATIONS

BREATH ANALYSIS USING MICROSENSORS

A MicroSensor Array for Exercise and Health Monitoring
John Glenn Biomedical Engineering Consortium (JGBEC)

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Chicago, IL

MEI Makel Engineering Inc.

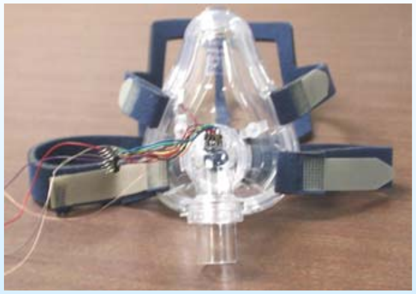
THE CLEVELAND CLINIC FOUNDATION

CWRU

NASA

A MicroSensor Array for Exercise and Health Monitoring John Glenn Biomedical Engineering Consortium (JGBEC)

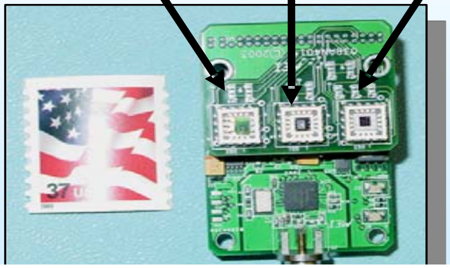
- **EXPAND ON PREVIOUS BREATH ANALYSIS WORK**
- **USE ARRAY OF SENSORS OF VERY DIFFERENT TYPES TO MONITOR BREATH FOR EXERCISE AND HEALTH**
  - **CO2 and O2 MONITORING WILL BE EXPANDED TO INCLUDE NOx, H2S, HYDROCARBONS, CO, pH, and T**
  - **NASA GRC, CLEVELAND CLINIC FOUNDATION, MAKEL ENGINEERING, TRANSDUCERS INC, CASE WESTERN RESERVE UNIVERSITY**
- **USE GAS PATTERN MEASURED FOR EXERCISE PARAMETERS BUT ALSO AS INDICATORS OF OVERALL HEALTH**
- **EVALUATE MATURITY OF PRESENT MICROSENOR TECHNOLOGY FOR BREATH MONITORING APPLICATIONS**



Hydrocarbon Sensor

Oxygen Sensor

Hydrogen Sensor



Lick and Stick Sensor System

MEI Makel Engineering Inc.

THE CLEVELAND CLINIC FOUNDATION

CWRU

NASA

Breath Sensor System Overview

Sensor operates using PDA
or Laptop for user interface

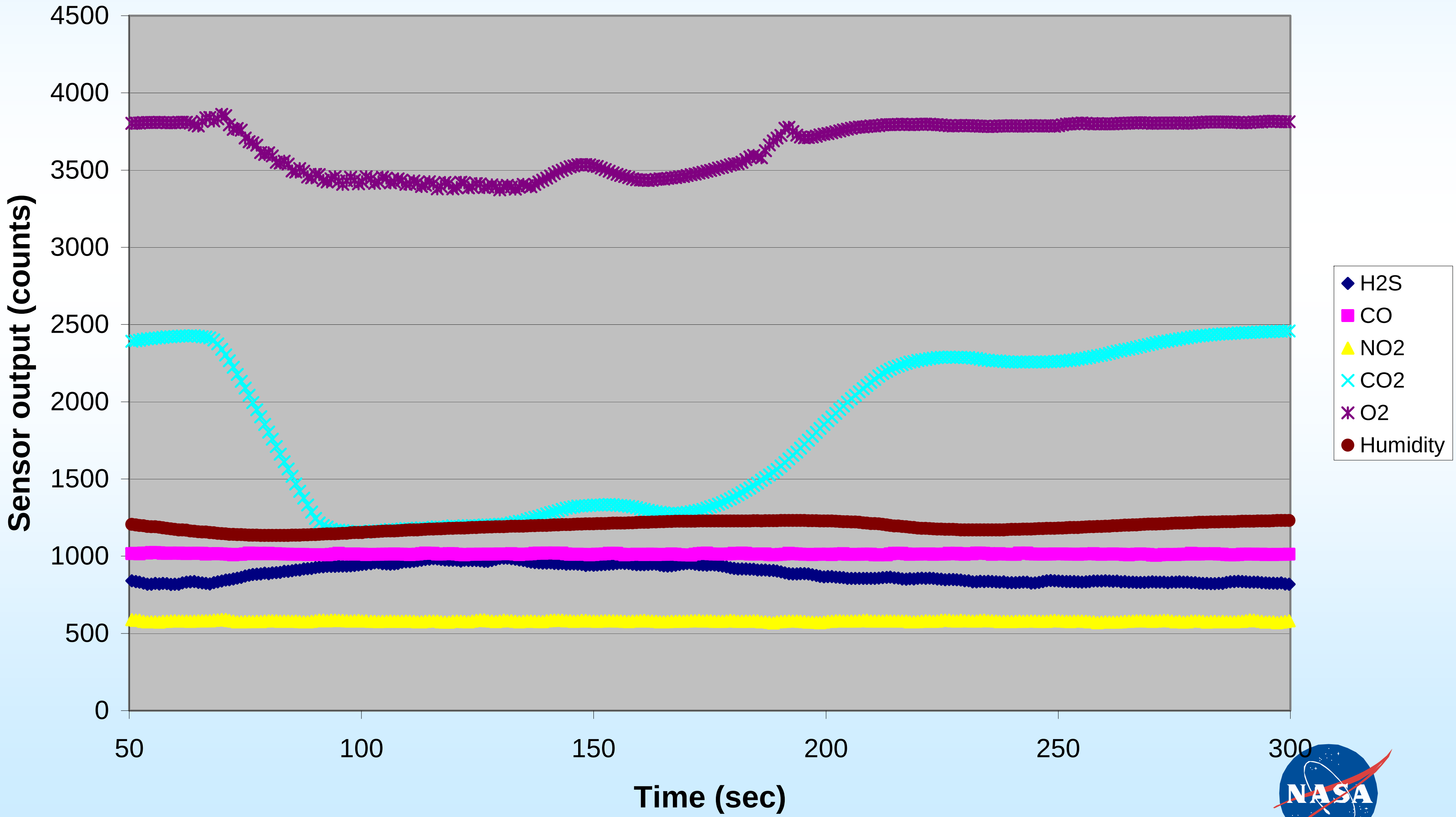
Breath Sensor System – includes mouthpiece for breath collection, Nafion drying tube in sample line, sensor manifold with PDA interface, and mini sampling pump

•Sensors

- •CO_2 – Solid State - Lithium Phosphate, migrate to Nafion based sensor
- •O_2 – Nafion based sensor
- •CO – Wet Electrochemical Cell
- •NOx – Wet Electrochemical Cell
- •H_2S – Wet Electrochemical Cell

Breath Sensor Response Data

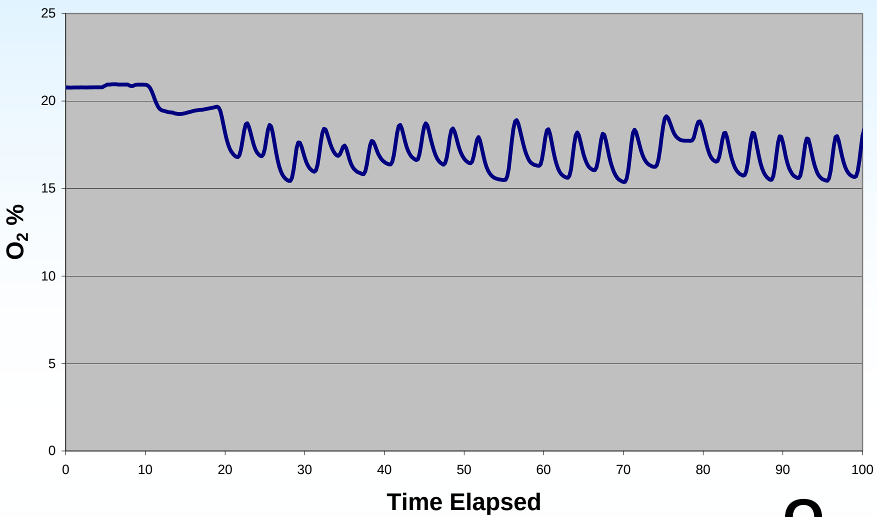
- Testing at Cleveland Clinic Foundation and Makel Engineering, Inc.
  - Comparison to clinical test equipment
- Baseline lab test results show response to O_2, CO_2 during breathing
  - –Small response from CO sensor, no response from H_2S or NOx



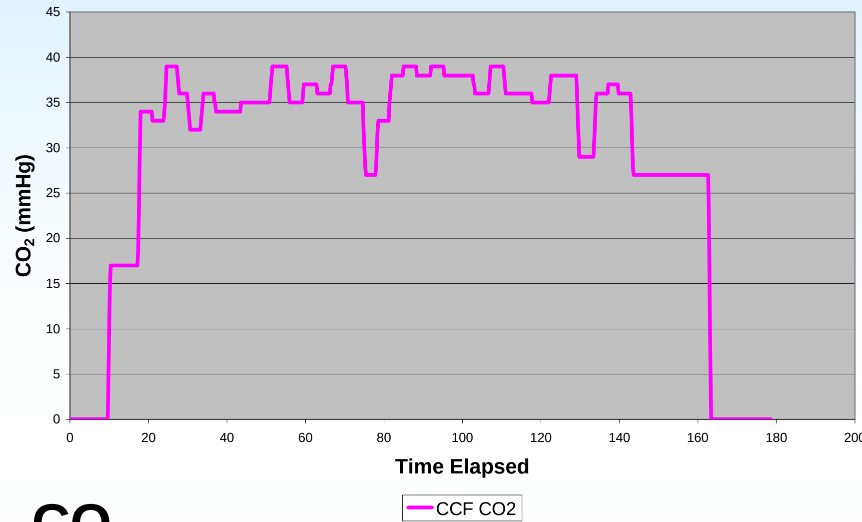
Breath Sensor Response Data

HIGHER TEMPERATURE CO2 AND O2 SENSORS PROVIDED RESULTS COMPARABLE TO THAT OF LAB BENCH INSTRUMENTATION

O_2 Analyzer Response



Benchtop CO_2 Monitor

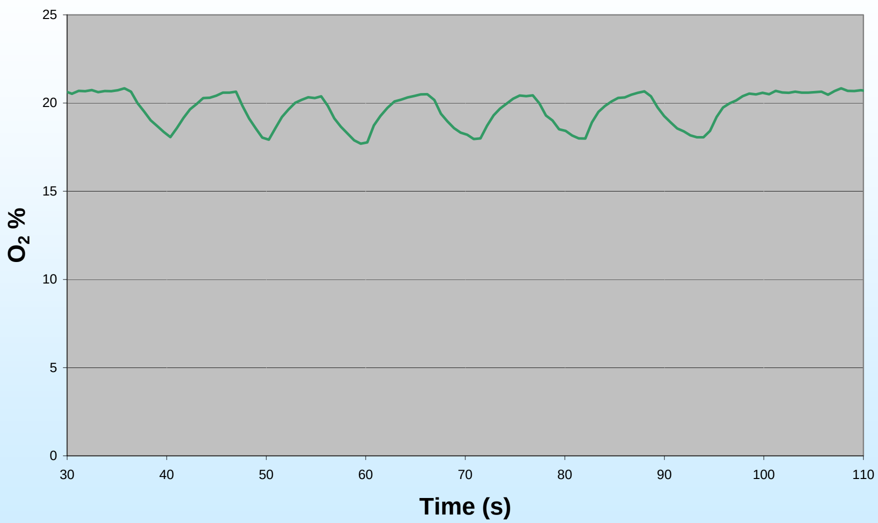


Analyzer

O_2

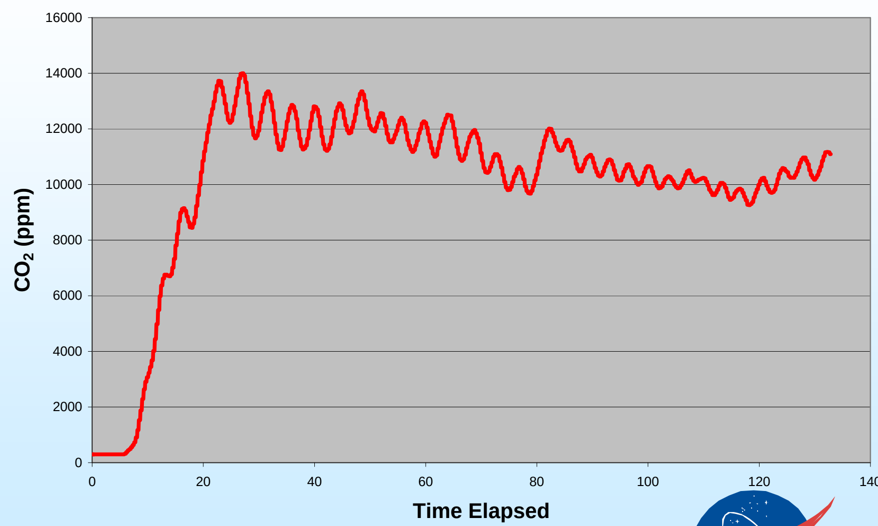
CO_2

O_2 Sensor response



Sensor

CO_2 Sensor Breath by Breath Response



JBEC SENSOR ARRAY TASK CONCLUSION

- THE PROJECT FABRICATED, TESTED, AND DELIVERED AN INTEGRATED BREATH MONITORING SENSOR SYSTEM INCLUDING AN ARRAY OF GAS MICROSENSORS, DATA ACQUISITION AND DISPLAY UNIT, SAMPLE PUMP, AND MOUTHPIECE.
- SIGNIFICANT MINIATURIZATION OF THE TESTING SYSTEM OCCURRED AND THE COMPLETE SYSTEM WAS CHARACTERIZED AT THE CLEVELAND CLINIC FOUNDATION INCLUDING PATIENT TESTING, AND AT MAKEL ENGINEERING, INC.
- OVERALL THIS WORK HAS EVALUATED THE MATURITY AND CAPABILITY OF MICROSENSORS TO REPLACE LAB RACK SIZED EQUIPMENT WITH A MINIATURIZED METABOLIC GAS MONITOR SYSTEM.
- TESTING DEMONSTRATED THAT THE HIGHER TEMPERATURE O2 AND CO2 SENSORS PROVIDE THE FUNCTIONALITY REQUIRED FOR A BREATH MONITORING SYSTEM.
  - CAN IN PRINCIPLE BE USED TO REPLACE LAB RACK SIZED EQUIPMENT WITH PORTABLE SYSTEMS. THESE CHEMICAL SPECIES ARE CONSIDERED THE HIGHEST PRIORITY MEASURE-MENTS IN EXERCISE PHYSIOLOGY.
  - TESTS WITH LESS MATURE SENSOR TECHNOLOGY WERE EITHER IN-CONCLUSIVE OR POINTED TO SPECIFIC DESIGN CHANGES.

FUTURE DIRECTIONS

CUTTING EDGE TECHNOLOGY IMPLEMENTATION SUGGESTIONS

- WHILE THE USER MIGHT LEVERAGE SENSOR TECHNOLOGY BEING DEVELOPED ELSEWHERE, UNIQUE PROBLEMS REQUIRE SPECIALIZED SOLUTIONS.
  - BIOMEDICAL APPLICATIONS PRESENT SIGNIFICANT UNIQUE CHALLENGES
- FULL FIELD DESIGN APPROACH: SENSORS SYSTEMS COMBINED WITH ELECTRONICS AND SOFTWARE FOR DATA PROCESSING AND INTERPRETATION FROM THE BEGINNING
  - AVOID PUTTING MAJOR SYSTEM COMPONENTS ON AS AN AFTERTHOUGHT
  - COMPLETE TEAM APPROACH DURING DEVELOPMENT INCLUDING BOTH DEVELOPERS AND USERS
  - UNDERSTAND REQUIREMENTS EARLY
- DESIGN SENSOR SYSTEM TO OPTIMIZE MEASUREMENT OF MULTIPLE PARAMETERS SIMULTANEOUSLY TO IMPROVE FULL-FIELD SYSTEM INFORMATION AND MEASUREMENT RELIABILITY
- DEVELOP SENSOR SYSTEMS WHICH INCLUDE INTEGRATED INTELLIGENCE WHILE MINIMIZING SIZE, WEIGHT, AND POWER CONSUMPTION.
  - PROVIDE THE USER WHAT THEY WANT TO KNOW
  - HAVE THE BACKGROUND MATERIAL AVAILABLE
  - PROVIDE BUILT-IN CALIBRATION AND SELF-TEST
  - BRING INTELLIGENCE DOWN TO LOWEST COMPONENT LEVEL FEASIBLE
- DEMONSTRATE TECHNOLOGY RELIABILITY AND DURABILITY EXTENSIVELY BEFORE IMPLEMENTATION

LONG-TERM VISION

- **BREATH MONITORING CAN REVOLUTIONIZE HEALTH DIAGNOSIS AND CAN BE ENABLED BY INTELLIGENT MICRO/NANO SYSTEMS**
- **DESIGNER DIAGNOSTICS SYSTEMS TAILORED TO OPTIMIZE THE MEASUREMENT DOWN TO THE INDIVIDUAL PATIENT**
- **PART OF FULL FIELD DIAGNOSIS SYSTEM WHICH COULD ALSO BE ENABLED WITH INTELLIGENT MICRO/NANO SYSTEMS**
    - **IDEALLY WITH A RANGE OF NON-INVASIVE DIAGNOSTIC MEASUREMENTS**
    - **HEALTH DIAGNOSTICS SYSTEMS WHICH CAN SMELL, HEAR, SEE, FEEL, PROCESS INFORMATION AND COMMUNICATE, AND SELF-RECONFIGURE ALL IN MINIATURIZED FIELD APPLICABLE SYSTEMS**
- **DO SOMETHING WITH THE DATA: DIAGNOSIS COMBINED WITH TREATMENT**
- **NO MATTER HOW GOOD THE TECHNOLOGY, IT WILL NOT BE USED UNTIL IT PROVES ITSELF**

**A POSSIBLE VISION:
A "SMART" SUIT ABLE TO PROVIDE COMPLETE DIAGNOSTICS AND HEALTH CARE**

ACKNOWLEDGMENTS

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