Development of a Venus Surface Wind Sensor

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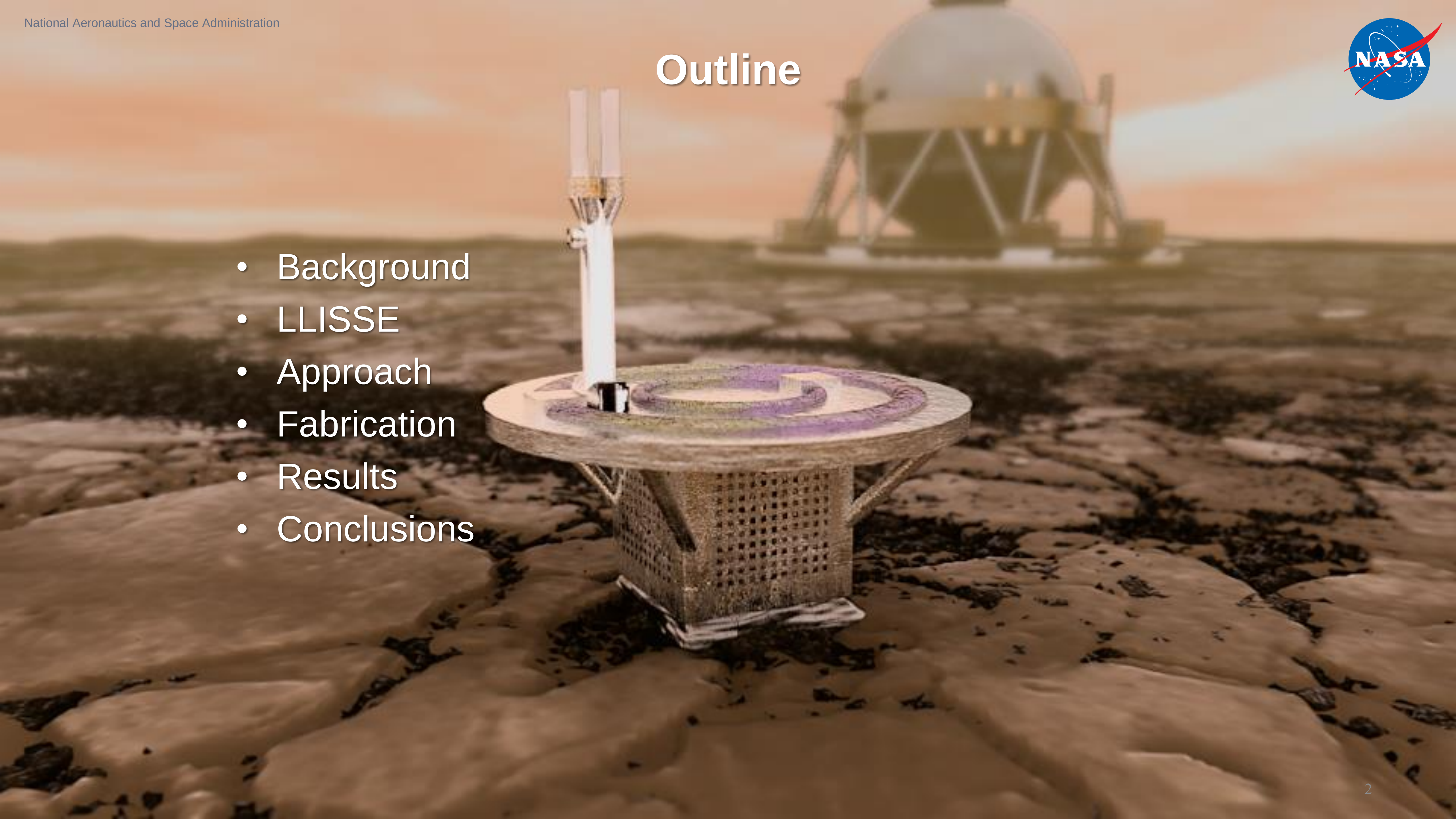
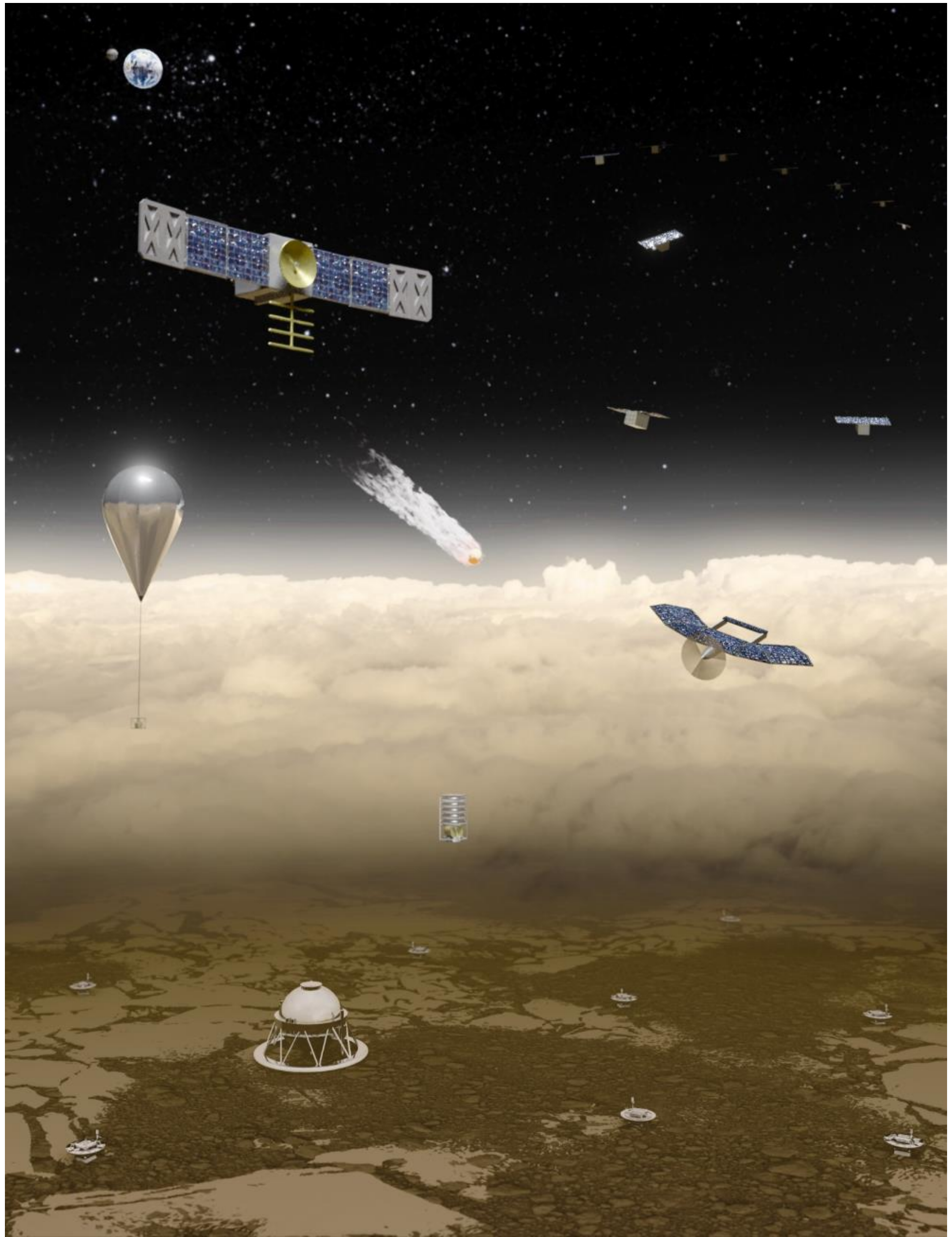
Outline

- Background
- LLISSE
- Approach
- Fabrication
- Results
- Conclusions



Introduction

- The ability to measure the wind on the surface of Venus and track changes over a long time period is key to better understand the planet's atmospheric structure and dynamics
  - Venus has a very hostile environment with an average surface temperature of 465 °C and surface atmospheric pressure of 90 atm. in the presence of corrosive species
  - Missions that have landed on the surface of Venus have typically lasted at most ~2 hours due to the high temperatures and harsh conditions
  - Long term measurement of Venus planetary conditions has been limited by the lack of electronics, communications, power, sensors, instrument, and actuation systems operational in the harsh Venus environment
  - New technologies are under development that will impact long-duration Venus exploration



Development of a Venus Surface Wind Sensor

BACKGROUND

Smart Sensing and Electronics Systems Branch (LCS)

Description

Conducts research and development of **adaptable instrumentation to enable intelligent measurement systems** for ongoing and future aerospace propulsion and space exploration programs. Emphasis is on smart sensors and electronics systems for diagnostic engine health monitoring, controls, safety, security, surveillance, and biomedical applications**; often for high temperature/harsh environments**.

Microsystems Fabrication Facility

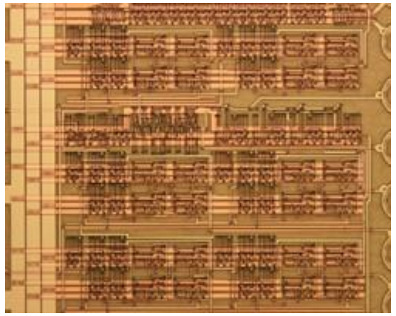
Core Capabilities (technical areas)

- Silicon Carbide (SiC) - based electronic devices
  - Sensors and electronics for high temp (600°C) use
  - Wireless sensor technologies, integrated circuits, and packaging
- Micro-Electro-Mechanical Systems (MEMS)
  - Pressure, acceleration, fuel actuation, and deep etching
- Chemical gas species sensors
  - Leak detection, emission, fire and environmental, and human health monitoring
- Microfabricated thin-film physical sensors
  - Temperature, strain, heat flux, flow, and radiation measurements
- Harsh environment nanotechnology
  - Nano-based processing using microfabrication techniques
  - Smart memory alloys and ultra low power devices

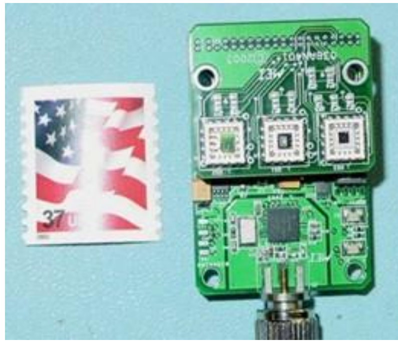
Facilities/Labs

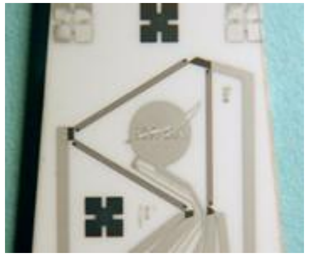
- Microsystems Fabrication Facilities
  - Class 100 Clean Room
  - Class 1000 Clean Room
- Chemical vapor deposition laboratories
- Chemical sensor testing laboratories
- Harsh environment laboratories
  - Nanostructure fabrication and analysis
  - Sensor and electronic device test and evaluation

SiC Signal Processing



Chemical Sensors





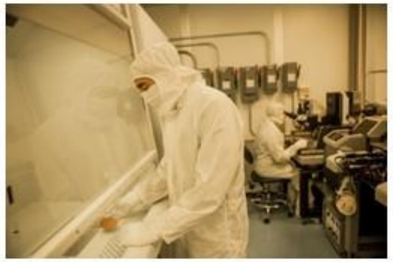
Thin Film Physical Sensors

NASA Glenn Research Center (GRC) Microsystems Fabrication Laboratory

The Only Facility To Have Fabricated Long-lived High Temperature (>500º C) Electronics

- **Demonstrated, unique capability to fabricate 500˚C durable circuits of moderate complexity operational for extended period**
- **Design and build approach of a broad range of circuits based on the core technology potentially enabled by this work.**
- **Circuit fabrication and packaging based on these capabilities can be included as part of a proposal, assuming inclusion of associated costs.**
- **Circuit design choices limited. Identification and preliminary design of circuit by collaborator assumed. Feedback from NASA GRC on feasibility and costs can be provided for a proposal as appropriate.**
- **Please see https://www1.grc.nasa.gov/facilities/microfab/ for more information.**

- 2500 square feet class 100 and 1000 cleanroom.
- Supports microfabrication of harsh environment sensors and integrated circuits.
- Physical vapor deposition, Oxidation and annealing, Chemical vapor deposition and plasma etching capabilities.
- Extensive microelectronics processing with photomask aligners & wet chemical etching stations



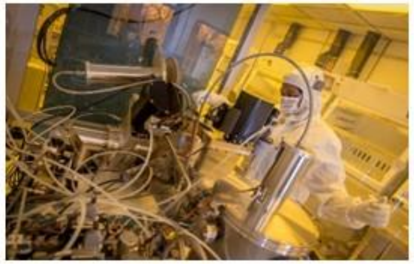
Wet Chemical Work Stations and Mask Aligner

Ultra High Vacuum Metal Deposition System

Oxidation and Annealing Furnaces and Silicon Dioxide Low Pressure Chemical Vapor Deposition System

Probe Test Station

Rapid Thermal Annealer



Reactive Ion Etcher

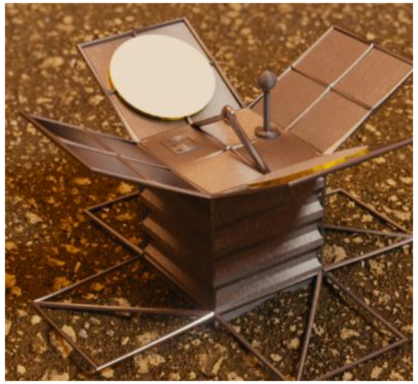
Inductively Coupled Plasma Etcher (Background) and Chemical Work Stations

Tantalum Silicide Sputter Deposition System

HARSH ENVIRONMENT ELECTRONICS AND SENSORS APPLICATIONS

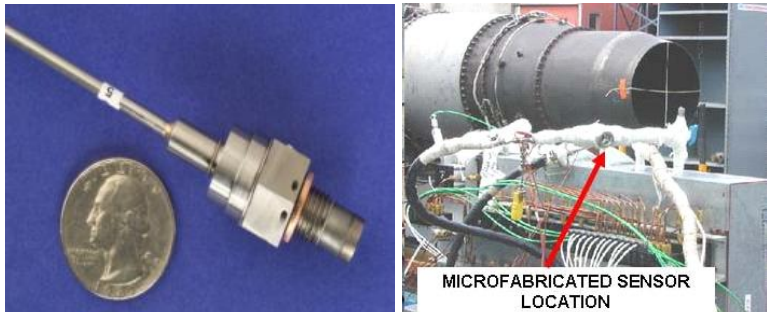
World Leading in Both Electronics and Sensors

- **Needs:**
  - **Operation In Harsh Environments**
  - **Range Of Physical And Chemical Measurements**
  - **Increase Durability, Decrease Thermal Shielding, Improve In-situ Operation**
- **Response: Unique Range Of Harsh Environment Technology And Capabilities**
  - **Standard 500˚C Operation By Multiple Systems**
  - **Temperature, Pressure, Chemical Species, Wind Flow Available**
  - **High Temperature Electronics To Make Smart Systems**
- **Enable Expanded Mission Parameters/In-situ Measurements**
- **Long Lived High Temperature Electronics At 500˚C**

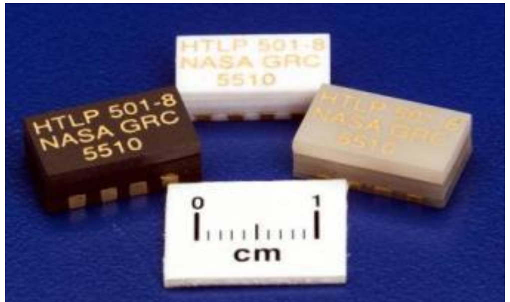


Long Lived In-Situ Surface Explorer (LLISSE)

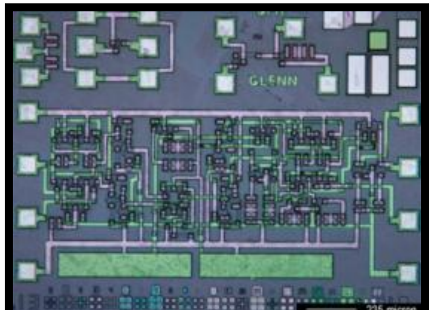
Range of Physical and Chemical Sensors for Harsh Environments



Harsh Environment Packaging (10,000 hours at 500˚C)



High Temperature Signal Processing and Wireless

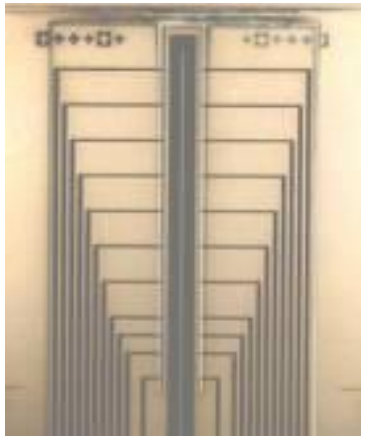


Moving Towards: High Temperature "Lick and Stick" Systems

Thin Film Physical Sensors for High Temperature Applications

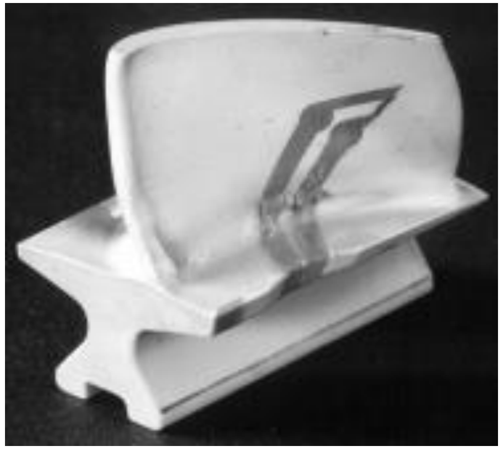
Advantages for temperature, strain, heat flux, flow & pressure measurements:

- Negligible mass & minimally intrusive (microns thick)
- Applicable to a variety of materials including ceramics
- Minimal structural disturbance (minimal machining)
- Intimate sensor to substrate contact & accurate placement
- High durability compared to exposed wire sensors
- Capable for operation to very high temperatures (>1000°C)



Flow sensor made of high temperature materials

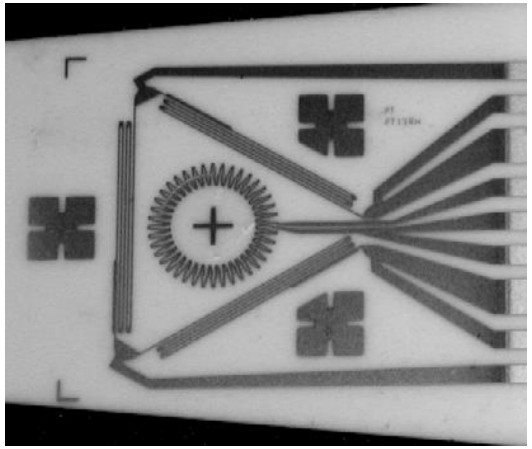
Multifunctional smart sensors under development



PdCr strain sensor to T=1000°C

Pt- Pt/Rh temperature sensor to T=1200°C

Heat Flux Sensor Array to T=1000°C



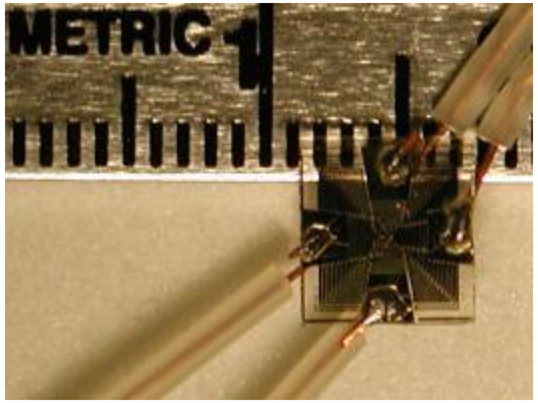
Multifunctional Sensor Array

GRC Physical Sensor Research Developments

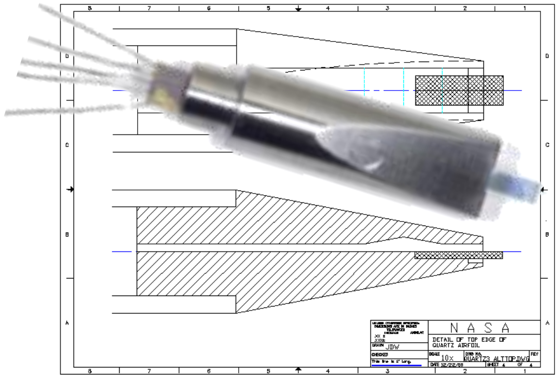
- R&D 100 Awards in 1991, 1995, and 1998
- NASA Group Achievement Awards in 2003 and 2015
- NASA Tech Briefs *Create the Future Design Contest* Award 2008
- 2013 Sensors Expo Applications Award
- Partnerships in Sensor Development:

ROLLS ROYCE
Pratt & Whitney
PIWG
GOODYEAR
University of Rhode Island

1998 R&D 100 Award
Long-lived Convoluted Thermocouples For Ceramic Temperature Measurements



2008 NASA Tech Briefs Create the Future Design Contest - Machinery & Equipment
Flexible Small Area Heat Flux Sensor developed for Goodyear Tire & Rubber Co.

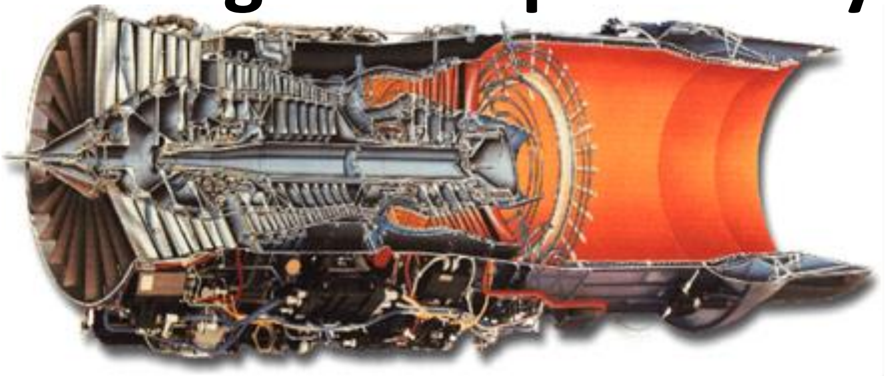


2003 NASA Group Achievement Award
SiC High Temperature Drag Force Transducer as part of the Integrated Instrumentation & Testing Systems project

2015 NASA Group Achievement Award
Thin-Film thermocouple sensor prototype operation validated as part of the Vehicle Integrated Propulsion Research project

Technology to Benefit Aero and Space Missions

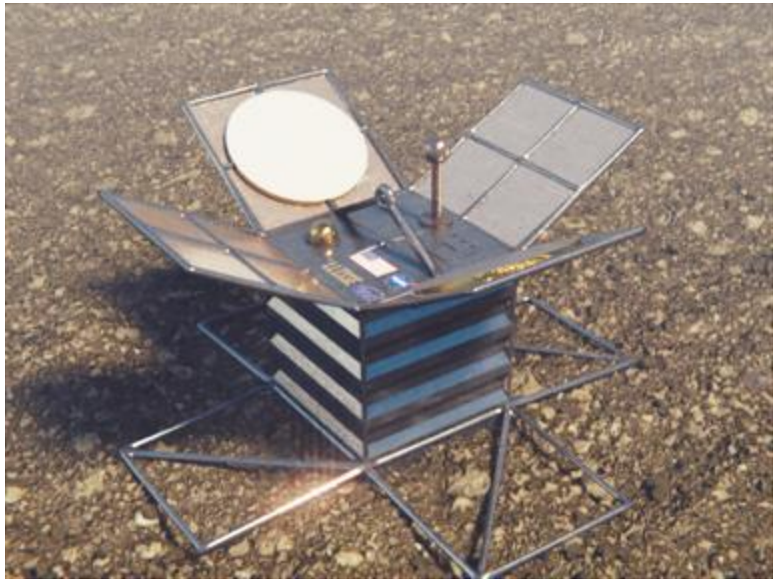
Intelligent Propulsion Systems



T > 450 °C sensors with electronics in key engine areas for improving performance
- Thrust to weight ratio
- Fuel efficiency & emissions

Power devices for electric actuation

Venus Exploration Landers



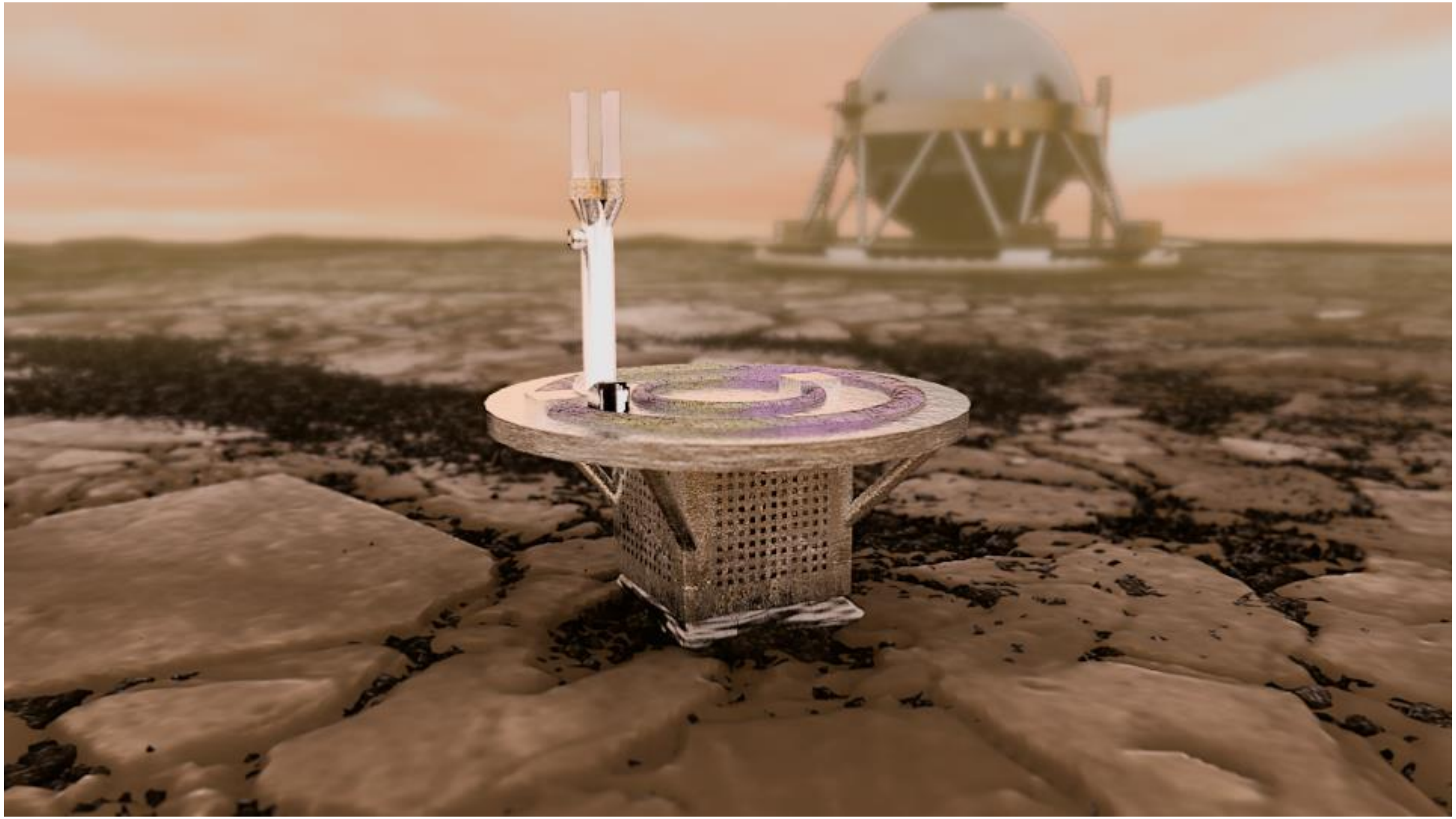
Long-duration landers must live in **460 °C**, 92 atm. caustic chemistry

Development of a Venus Surface Wind Sensor

LLISSE

Long-Lived In-Situ Solar System Explorer (LLISSE)

PI: Tibor Kremic, NASA Glenn



Long-Lived In-Situ Solar System Explorer (LLISSE)

LLISSE is a small (~10kg) probe being developed to acquire and transmit simple but important science measurements for extended periods from the surface of Venus

- LLISSE is a small and “independent” probe for Venus surface applications
- LLISSE acquires and transmits simple but important science
- Three key elements leveraged
  - Recent developments in high temperature electronics
  - Focused, low data volume measurements
  - Novel operations scheme

LLISSE Science Objectives and Traceability

Decadal Survey Goals	LLISSE Science Objectives	Measurements	Instrument Requirements
A) Define the current climate on the terrestrial planets	1) Acquire temporal meteorological data	Measurement of p, T, u, v and light	3-axis wind sensor measurements, radiance
	2) Estimate momentum exchange between the surface and the atmosphere	Same as above	Same as above
B) Understand chemistry of the middle, upper and lower atmosphere	3) Determine the key atmospheric species at the surface over time	Measure the abundance of gases H_2O, SO_2, CO, HF, HCl, HCN, OCS, NO, O_2	Chemical sensor measurements
C) Determine how solar energy drives atmospheric circulation and chemical cycles	4) Determine the rate of solar energy deposition at the Venus surface	Measure incident and reflected solar energy	Measurements of radiance

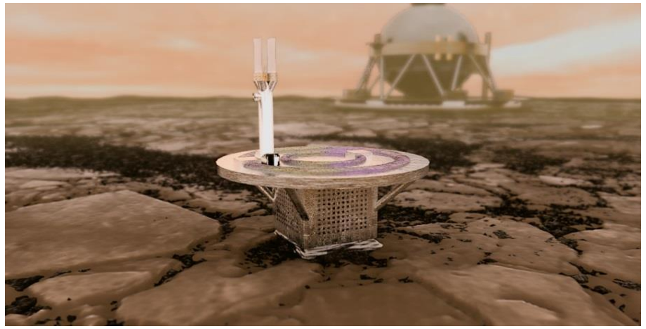
- Operations Goals:
  - Operate for a minimum ½ Venus solar day – capture one day/night transition
  - Take / transmit measurements periodically – timed for science need and to maximize transfer to orbiter / data relay
- LLISSE will also be a technology demonstrator for more sophisticated future long lived missions

LLISSE: Long-Lived Solar System Explorer

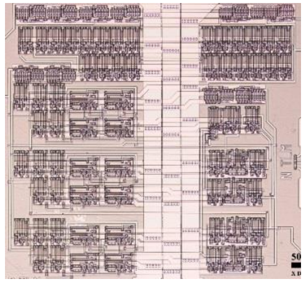
An Approach To Achieve A Class Of Long-lived Landers For Venus

Simple but important science from the Venus surface - for months

Potential Technology Demonstration version - Up to 10 days surface ops



Version of LLISSE in development ~10 kg and ~60 days life



500°C Durable 1000+ Transistor SiC IC

SAEVe Concept ~25 kg, ~40 cm dia, and 120 days life

All LLISSE's will be demonstrated at Venus surface conditions for intended life in GEER

NASA Glenn Extreme Environment Rig (GEER)

https://geer.grc.nasa.gov

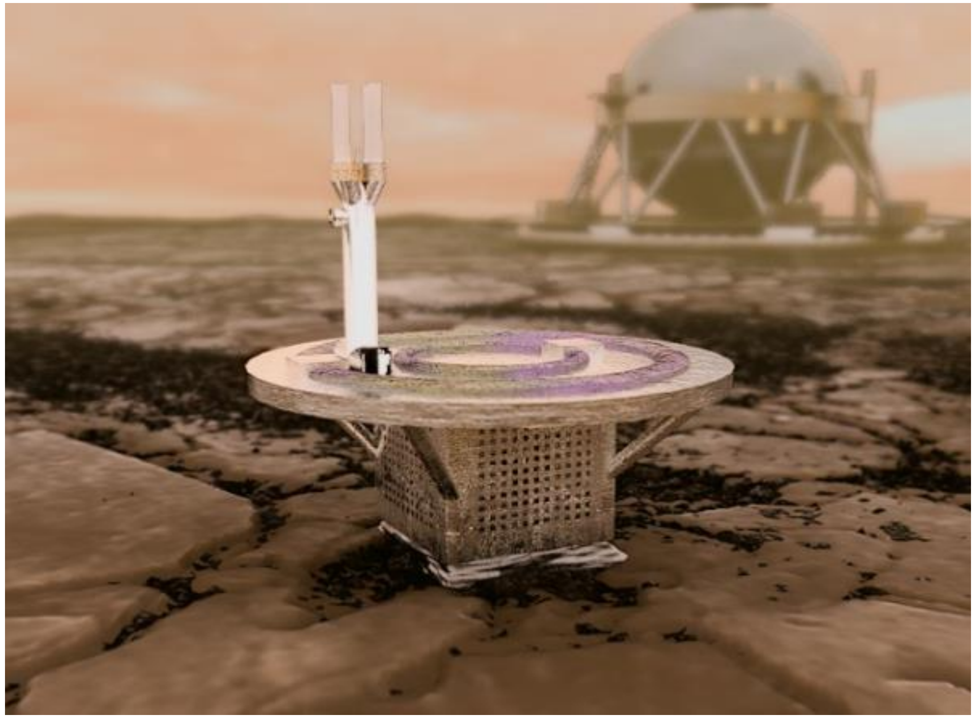
800-liter test chamber for high-fidelity simulation of Venus surface environment

- **First 10 chemical constituents of Venus atmosphere**
- 460 °C (860 °F), 1350 psia (~ 92 Earth atmospheres)
- Long duration (months) test runs

LLISSE mission requires long-life (at least 60 days) operations in full Venus surface conditions.

Intelligent Systems Introduction

- **LLISSE is a Complete, Compact, Stand-alone System Intended For Extended Operation On The Venus Surface**
- Intelligent Systems in the LLISSE Project Develops Three Core High Technologies for LLISSE Operation
  - Electronics for sensor control and monitoring, signal conditioning, data processing, and power management without use of an environmentally controlled enclosure.
  - Communications for data transfer from the Venus surface to an orbiter including circuit and antenna design. Determination of lander orientation.
  - Sensor systems for acquiring temporal meteorological and key atmospheric species data, momentum exchange between surface and atmosphere, and the rate of solar energy deposition.



Version of LLISSE in development ~10 kg and ~60 days life

Technology Development Overview

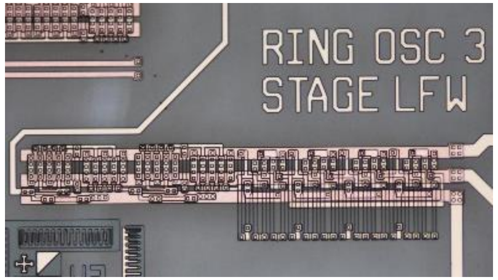
- Technologies relevant for Venus surface applications may often have their origin in other harsh environment applications e.g., aeronautics or industrial processing
- Material systems and engineering approaches standardly used for even harsh environment terrestrial applications may not be viable for Venus missions
- A major challenge is operation in Venus surface conditions without significant degradation and for extended periods of time
- Testing of proposed technologies in first at high temperature leading up to Venus simulated conditions include relevant chemistry, is core to technology advancement
- The status of Venus technology development is in some cases at the level of 1970's to 1980's technology; at these levels significant science can be accomplished.
- A mission needs a complete compliment of relevant technologies for success

GEER: 92 atm, 465 °C + chemical composition found at the surface of Venus (CO_2, N_2, SO_2, H_20, CO, OCS, HCl, HF, and H_2S)

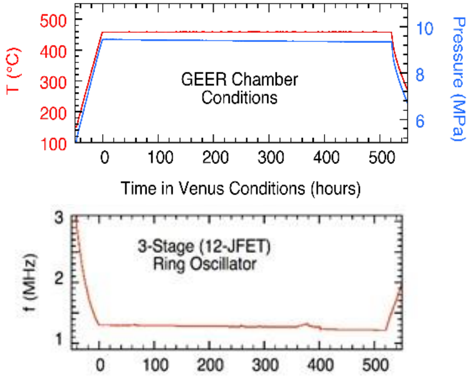
Paradigm Shift: Electronics Demonstrate Operability in Simulated Venus Conditions for 3 Weeks (2016)

- Previous operation of electronics in Venus missions has been limited to hours at most due to the extreme environment, and only in a protected pressure/temperature high mass (e.g., ~100s kg) enclosure.
- Unique capabilities have produced the World's First Microcircuits at moderate complexity with packaging that have the potential for long-lived unprotected operation at 500˚C.
- A SiC high temperature 12-transistor ring oscillator was demonstrated without protection from the simulated Venus surface conditions in the Glenn Extreme Environment Rig (GEER) for 21.7 days with good stability throughout the entire test.
- **This Venus surface demonstration of moderately complex electronics was a significant world record advancement, changed the possibilities for Venus surface exploration, and is a foundation for LLISSE**

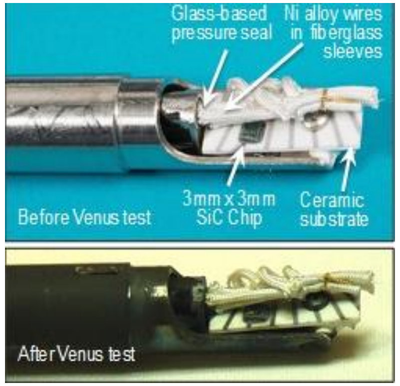
A SiC high temperature 12-transistor Ring Oscillator



High Temperature Ring Oscillator Continues Stable Operation in these Venus Simulated Conditions for 521 hours



SiC High Temperature Electronics Before And After Testing in Venus Surface Conditions: Rugged Operation for Extended Durations

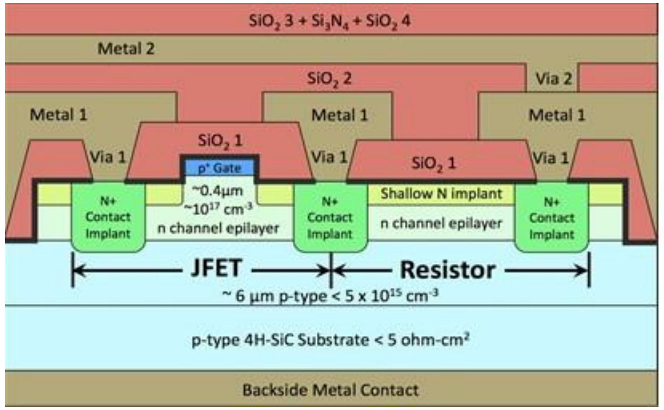


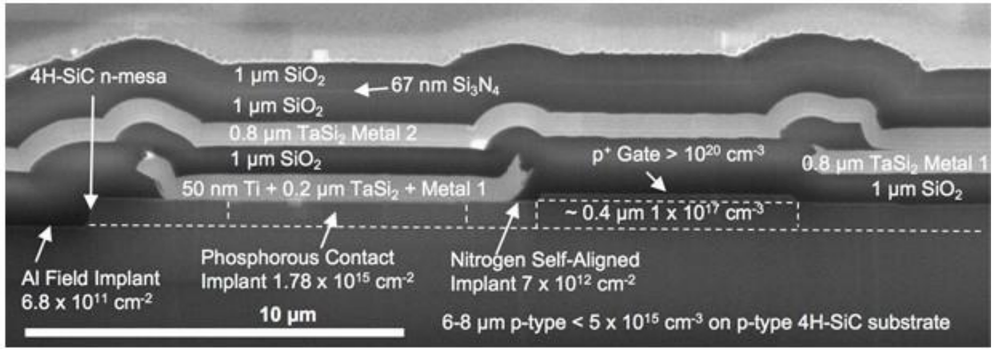
High Temperature Electronics Advancements

R&D 100 Award 2018

- *Unique capabilities have produced the World's First Microcircuits at moderate complexity (Medium Level Integration) that have the demonstrated long-lived operation at 500˚C*
- **Circuits contain 10's to ~1000 of Junction Field Effect Transistors (JFETs); An order of magnitude upscaling towards ~10000 JFETs/chip is under development.**
- **Enables a wide range of sensing and control applications *at High Temperatures***
  - **In-package signal conditioning for smart sensors**
  - **Signal amplification and local processing (digitization at the harsh environment source)**
  - **Wireless transmission of data**
- **A tool-box of signal conditioning, processing, and communications circuits are being developed and demonstrated**

Cross-sectional illustrations of NASA Glenn 4H-SiC JFET-R devices with two levels of interconnect. (a) Simplified device structure drawing. (b) Scanning electron micrograph of Generation 10 JFET source and gate region

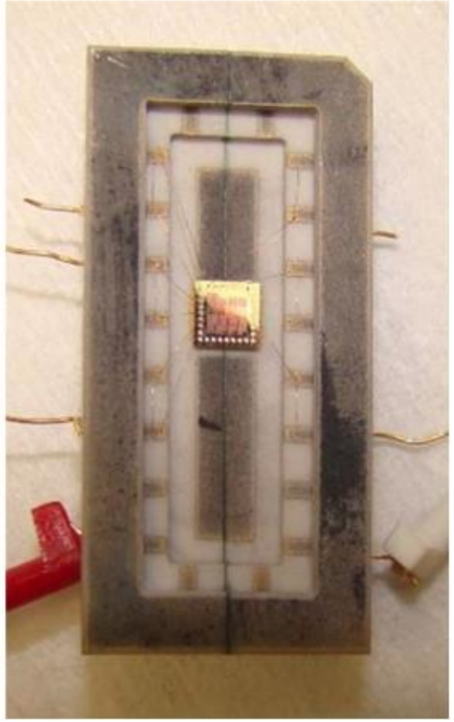


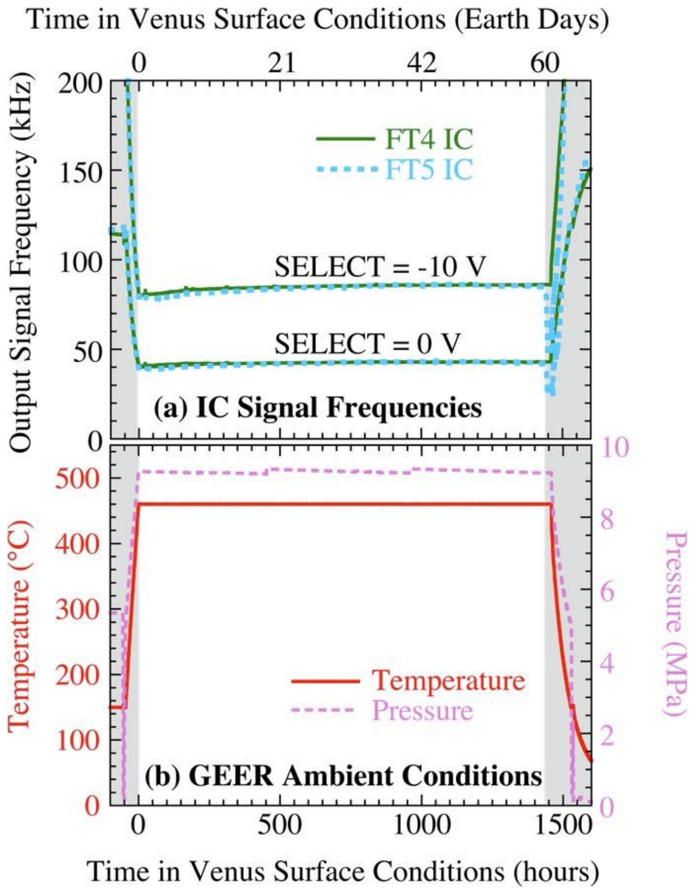


60-Day Venus Environment IC Test (in Glenn Extreme Environment Rig GEER)[1,2]

Before GEER

After 60 days GEER

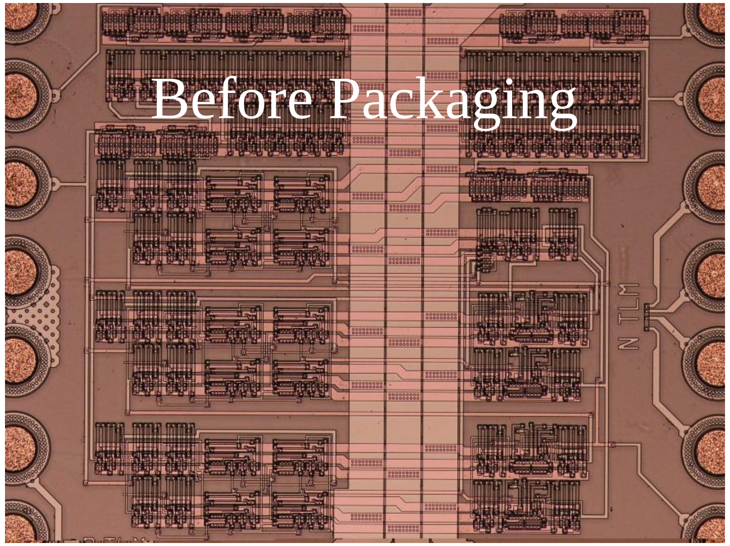


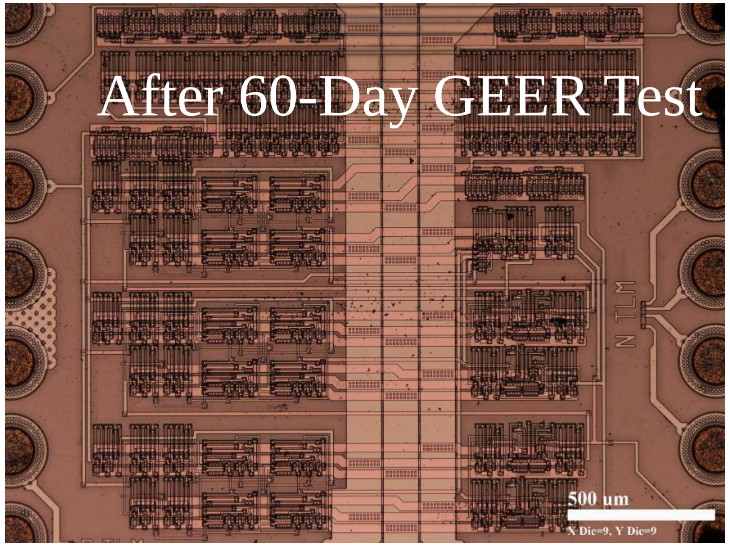


[1]Neudeck et al., IEEE J. Electron Devices Soc., vol. 1, p. 100 (2018).
[2]Chen et al., Proc. 2018 Int. High Temperature Electronics Conf.

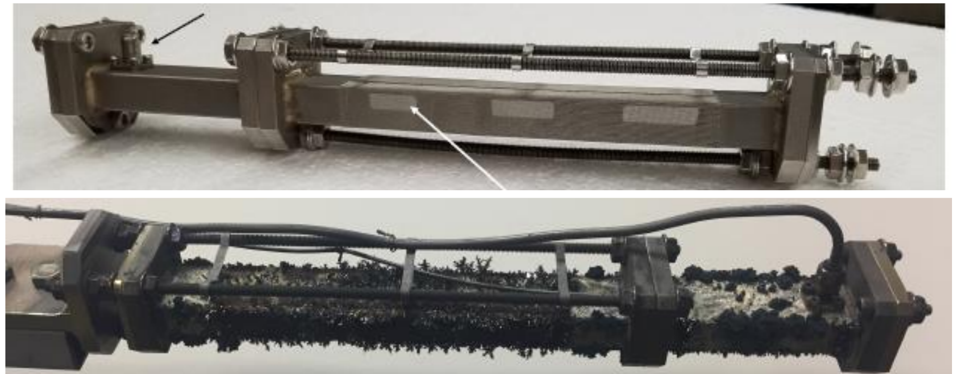
Material Choice (and GEER Testing) Matters

SiC Clock IC Chip Optical Microscope Photos
(These IC Materials Work - Chip operated for 60 days)





Wave Guide Before and After 60 Days of GEER Testing
(These materials react – grow crystals – will NOT work)



Evolving "Handbook" of Materials Reactions in Venus Surface Ambient

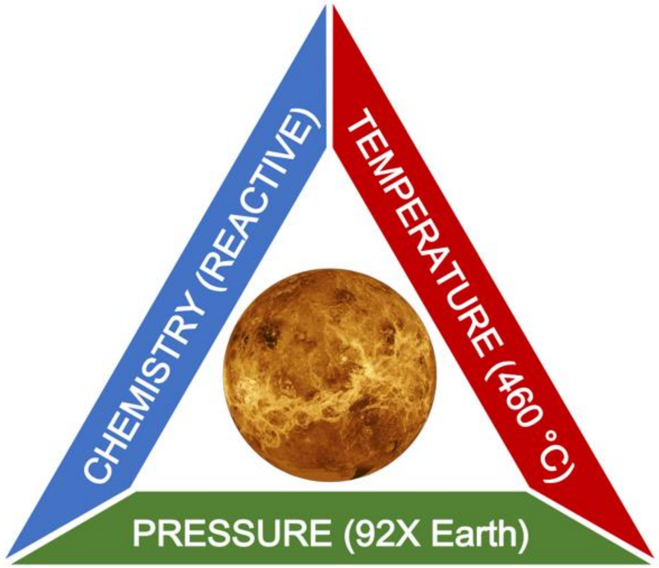
Table 1 What works and what doesn't

Devices	Materials	Outcome
Electronics Packaging	Pb	PbS
	Al_2O_3	No reaction
Insulation	CaO	$CaSO_3$, $CaSO_4$
SiC Electronics	Pt	PtS; fibers when present as thin film
	Pt (in the presence of Au)	PtS spheres
	Au	No reaction, but mobile
	Ir	No reaction, but mobile
	SiC	No reaction
	SiO_2	No reaction
Feedthrough Materials	Cu	Cu_2S crystals
	Ni	NiS crystals
	CuBe	Cu_2S crystals on surface
SiC Pressure Sensor	Kovar (Ni-Co-Fe)	NiS, Fe_xO_y
	AlN	No reaction
	Ag-Cu Braze	segregation into Cu_2S and Ag; Ag mobile
GEER Components	Inconel 625 (Ni-Cr-Mo-Fe)	NiS, Cr_xO_y
	304 SS	Mirror finish, low corrosion rate
	Al foil/Mg doped	MgO on surface, MgF inner layer, Al bulk no reaction

D. Lukco et al., Earth and Space Science 5, 270 (2018) https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2017EA000355

Long-Duration Wind Sensor Challenges

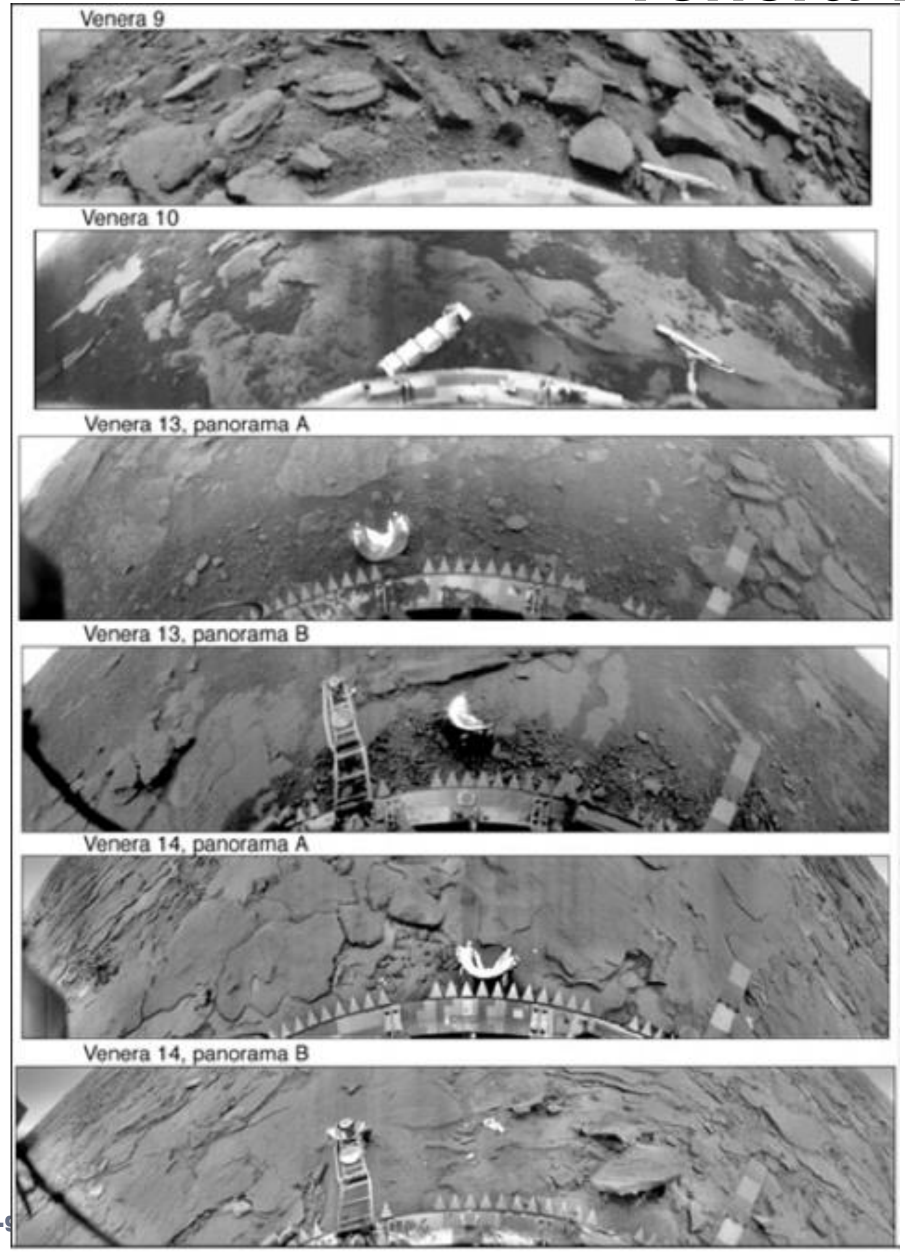
- For long-duration Venus surface missions such as the Long-Lived In-Situ Solar System Explorer (LLISSE) or the Seismic and Atmospheric Exploration of Venus (SAEVe), the challenge is to develop wind-sensing technology to survive the harsh environments for long periods as well as have minimal impact to the power and mass budgets of the lander.
- The challenge is to develop wind-sensing technology to survive for the 3000+ hours @500°C in high pressure CO_2/SO_2 atmosphere required for future Venus surface missions
  - Must be low power (<< 1 Watt), low mass (<< 1 kg)
  - Eliminates most standard technologies (hot-wire, pressure rakes)
- Turn to turbine engine instrumentation research technology for solutions



Development of a Venus Surface Wind Sensor

APPROACH

Venera Wind Measurements



- Venera 9: Very Rocky
  - Cup Anemometer: 0.4-0.7 m/s

- Venera 10: Fairly flat with gravel
  - Cup Anemometer: 0.8 m/s – 1.3 m/s

- Venera 13 Similar to 10
  - Acoustic microphone: 0.5 m/s

- Venera landers measured wind speeds on the Venus surface, averaging 0.6 m/s with sizable uncertainties up to ±50%

- Venera 14 Flat with some rocks – no gravel
  - Acoustic microphone: 0.3-.35 m/s

Drag-Force Anemometer

- A drag-force anemometer measures the bending deformation due to the force of a flow impinging on an extended cantilever beam using strain gauges.
- Miniature drag-force anemometer design first outlined in NASA TM X-3507 (Krauss & Fralick, 1977)
  - A drag-force anemometer measures the bending of an extended cantilever due to the force of a flow using thin film strain gauges
  - Applicable to steady state or turbulent flow
  - Not dependent on variable heat transfer
  - Low power requirement
  - Use multiple strain gauges in different orientations to detect changes in flow direction
- Design tested and validated in ground-based studies
  - Tests on turbofan engine inlet & bypass duct using several different configurations (NASA TM-81680, Krause & Fralick, 1981)
  - Drag-force anemometer validated in supersonic flow tests (AIAA J. 34 (1), Richard & Fralick, 1995)
  - Test of the drag force anemometer to look at frequency response in hot section (600°C) of a turbine engine (Okojie, Fralick, & Saad, 2003)

Turbine Flow Measurements

- Tests on turbofan engine inlet & bypass duct using several different configurations
- Sensors fabricated with metal and silicon beams with foil and semiconductor strain gauges (NASA TM-81680, Krause & Fralick, 1981)

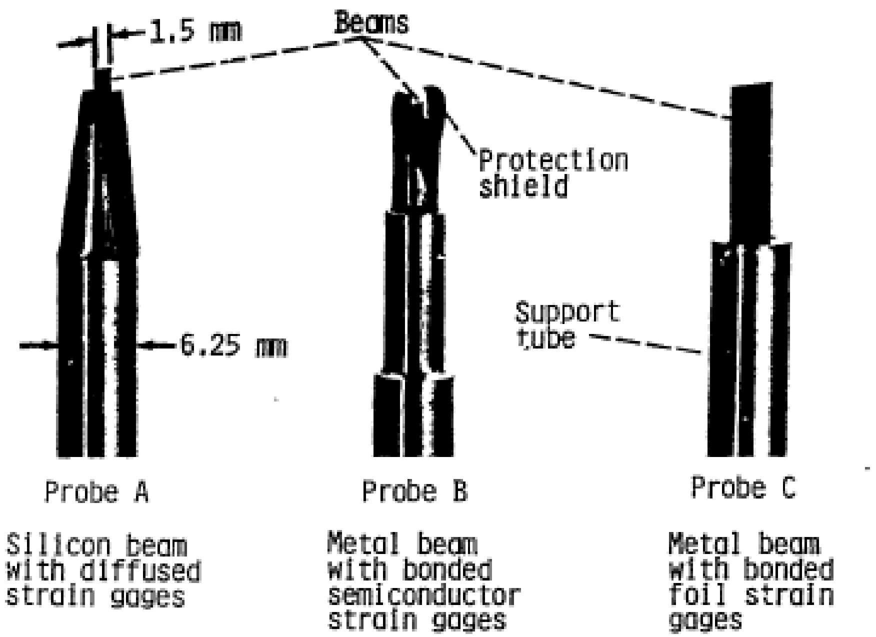


Figure 1. - Drag-Force anemometers.

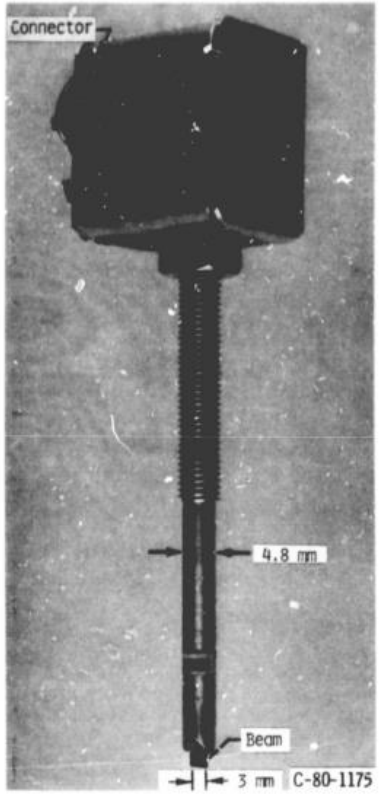


Figure 8. - Unsteady flow measurement probe for use in bypass duct of turbofan engine.

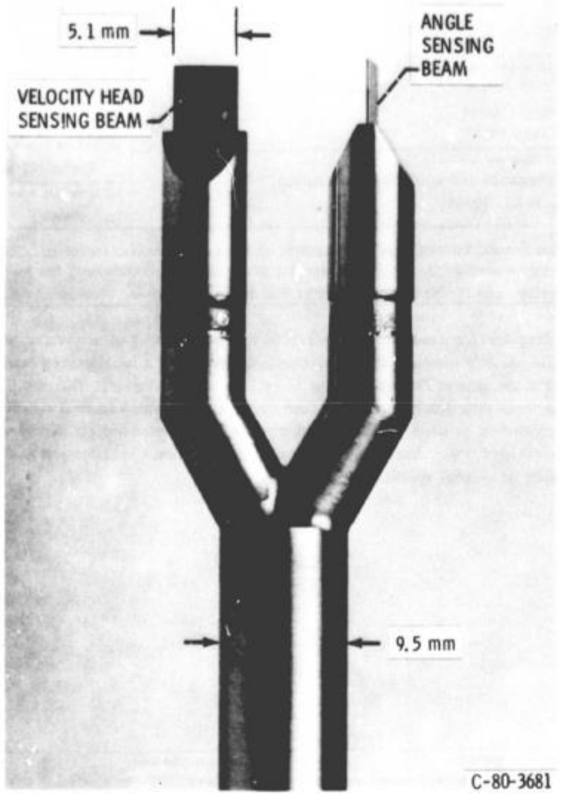
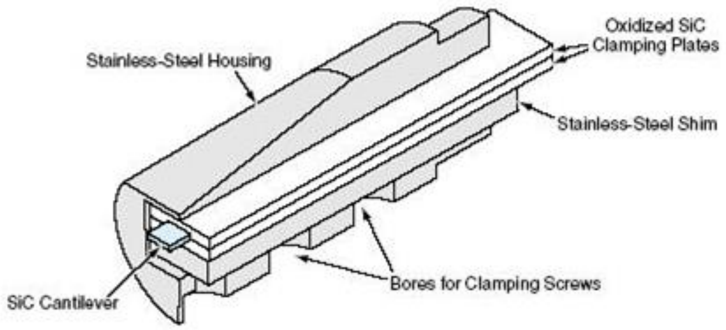


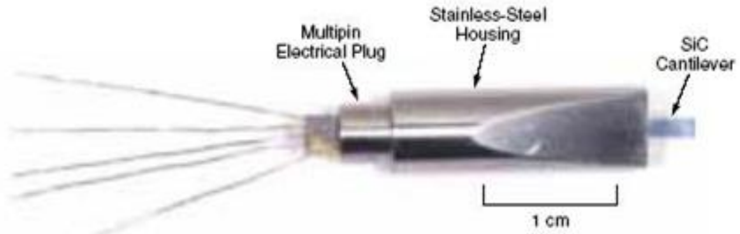
Figure 11. - Unsteady flow angle probe for use in turbofan engine inlet.

Turbine Flow Measurements

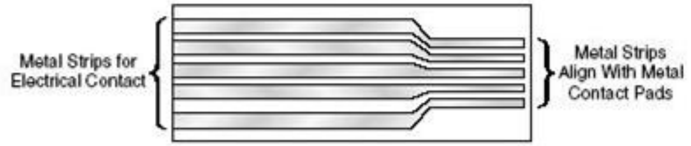
- Test of the drag force anemometer to look at frequency response in hot section (600°C) of a turbine engine.
- Sensor fabricated using 6H-SiC (p-type) with thin film piezoresistive strain gauges (Okojie, Fralick, & Saad, 2003)



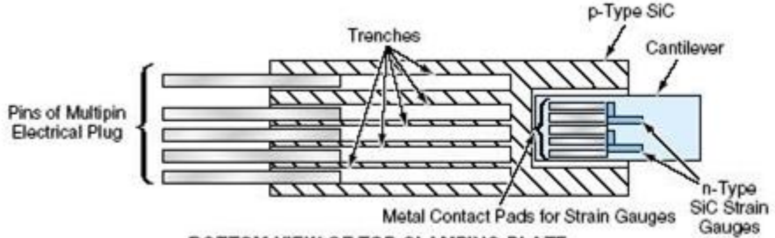
CUTAWAY DRAWING OF PACKAGED ANEMOMETER



PHOTOGRAPH OF PACKAGED ANEMOMETER
AND ELECTRICAL CONNECTIONS



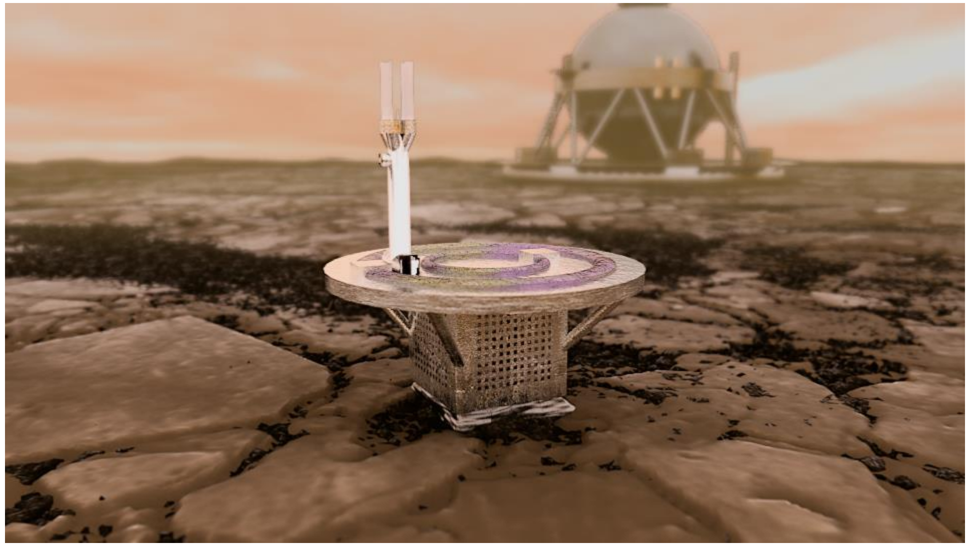
TOP VIEW OF BOTTOM CLAMPING PLATE MADE OF SiC



BOTTOM VIEW OF TOP CLAMPING PLATE
WITH CANTILEVER AND PLUG INSERTED

Adaption for Venus Application

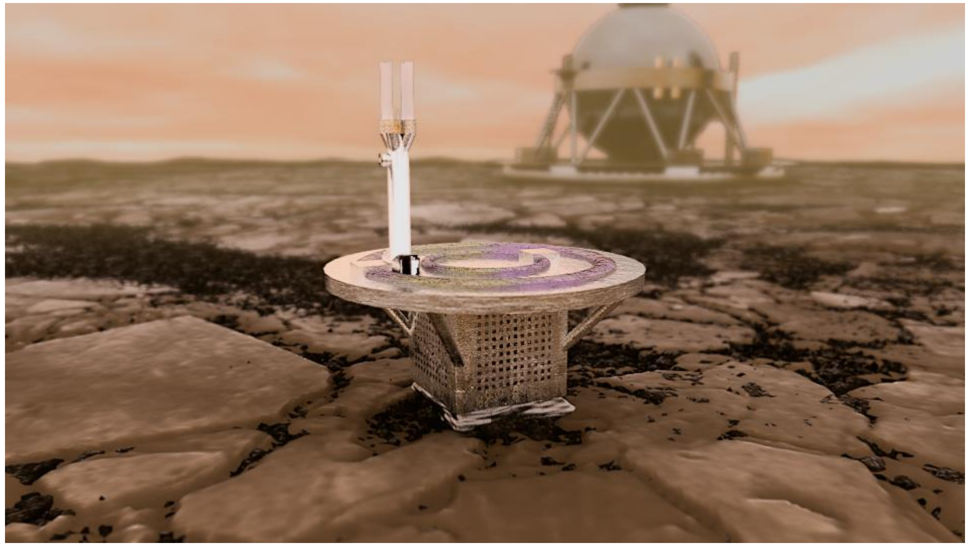
- Though the approach was demonstrated in aeronautic applications, the drag-force anemometers fabricated in these studies used material that would not survive in the harsh Venus surface environment.
- For Venus surface applications, cantilever beam and strain gauge materials were chosen to prevent reactivity with the corrosive atmosphere:
  - Alumina and sapphire (single crystal alumina) for the cantilever beam material
  - Gold film for the strain gauge
  - Stainless steel for the supporting structure



Specifications

For meaningful science on the Venus surface, the goals of the sensor are:

- Measure wind velocities in the range of 0.25 to 2.5 m/s, ±0.1 m/s
- Consume low power less than 10 mW
- Have mass less than 1 kg
- Operational for at least 60 days at Venus surface conditions
  - i.e. 465 °C in a high-pressure CO_2 supercritical atmosphere with a density of 67 kg/m^3, including chemically reactive species such as SO_2



Strain Analysis

- Stress σ on the cantilever beam impinged on by a flow with a drag force *D* is:

$$\sigma = E\varepsilon = \frac{6T}{wt^2}$$

  - E=Youngs modulus
  - ε = strain
  - t=thickness of beam
  - w=width of beam
- Moment T is found from D:

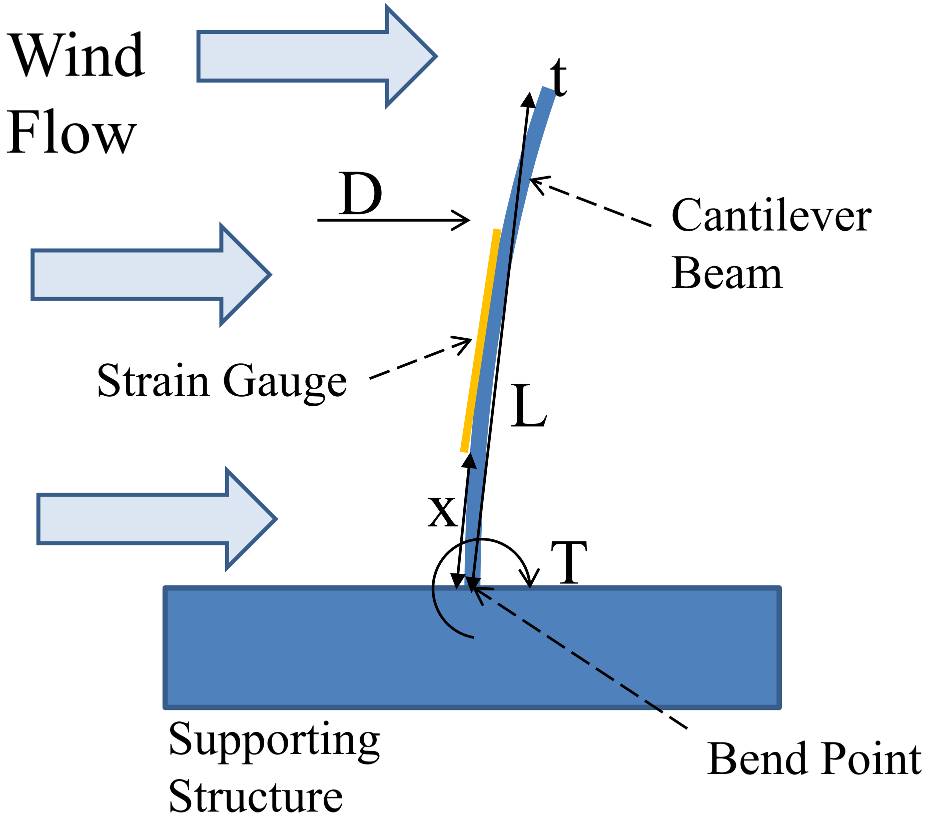
$$D = \frac{\partial T}{\partial l} = \frac{1}{2} C_d \rho l w U^2$$

  - Cd = drag coefficient
  - U = wind velocity
  - *l* = distance along the beam where the moment is determined
  - ρ = flow density
- Integrating over *l*:

$$T = \frac{1}{4} C_d \rho w U^2 L^2$$

- Maximum stress at bend point:

$$\sigma = \frac{3}{2} C_d \rho U^2 \frac{L^2}{t^2}$$



Strain Analysis

- Strain at the strain gauge at x is found from T:

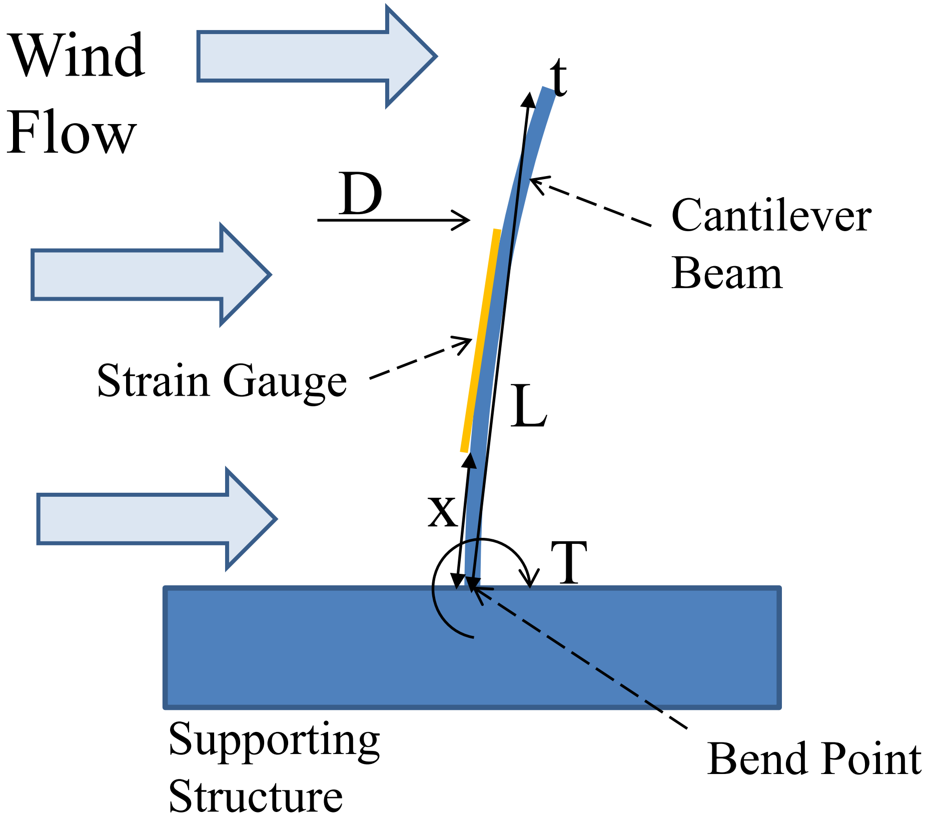
$$T(x) = \frac{1}{4} C_d \rho w U^2 \frac{L^2 - x^2}{2}$$

$$\sigma(x) = \frac{3}{4} C_d \rho U^2 \frac{L^2 - x^2}{t^2}$$

$$\varepsilon(x) = \frac{\sigma(x)}{E} = \frac{3}{4} C_d \rho U^2 \frac{L^2 - x^2}{E t^2}$$

- Wind velocity U from strain measurement is thus:

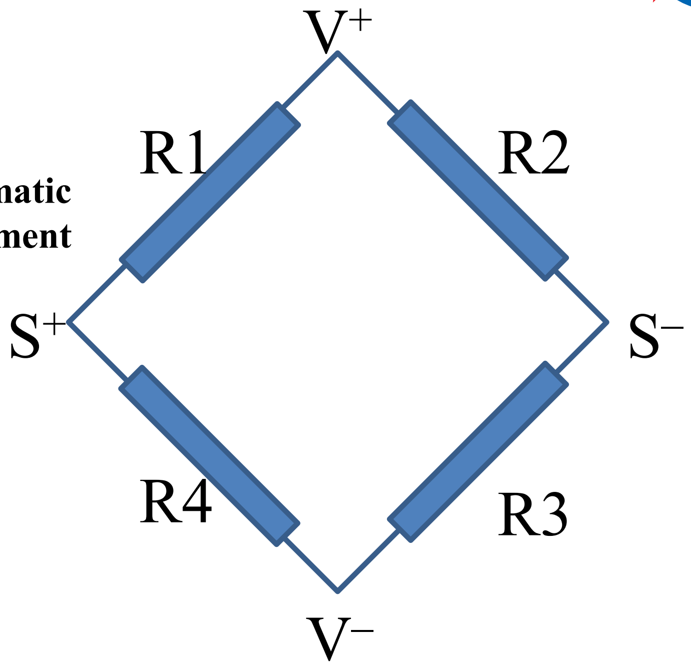
$$U = \left[\varepsilon(x) E \frac{t^2}{\frac{3}{4} C_d \rho \left(L^2 - x^2\right)} \right]^{1/2}$$



Strain Gauge Full Bridge

- R1, R3 aligned long length of beam parallel to bend
- R2, R4 perpendicular to bend
- Apply excitation Voltage V (= $V^+ - V^-$)
- Measure Signal S (= $S^+ - S^-$)
  - Leads resistance <1Ω
  - $gf \cdot \varepsilon = \Delta R/R$ (gf = Gauge Factor)
  - $\alpha = dR/R/dT$ (Temperature Coefficient of Resistance – TCR)
  - Expect R1=R2=R3=R4=R
- $S = V \cdot [gf \cdot \varepsilon] \cdot (1+\alpha\Delta T)$
- $\varepsilon = S/V/gf/(1+\alpha\Delta T)$

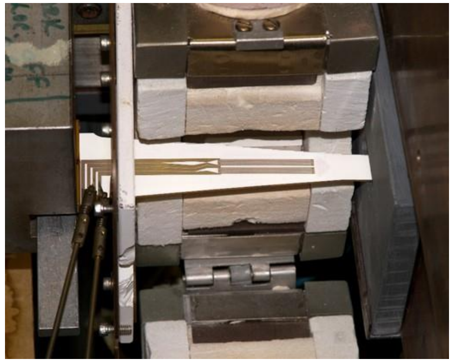
Full Bridge Schematic for Strain Measurement



Note:

- Resistances will not be *exactly* equal
  - Effective strain effects on signal due to net TCR to be subtracted from signal in analysis
- Test samples of thin film gold pattern on alumina at 465°C reveal gf=–35, TCR=2,400 ppm/°C

Specimen in fixture for Gf, TCR tests

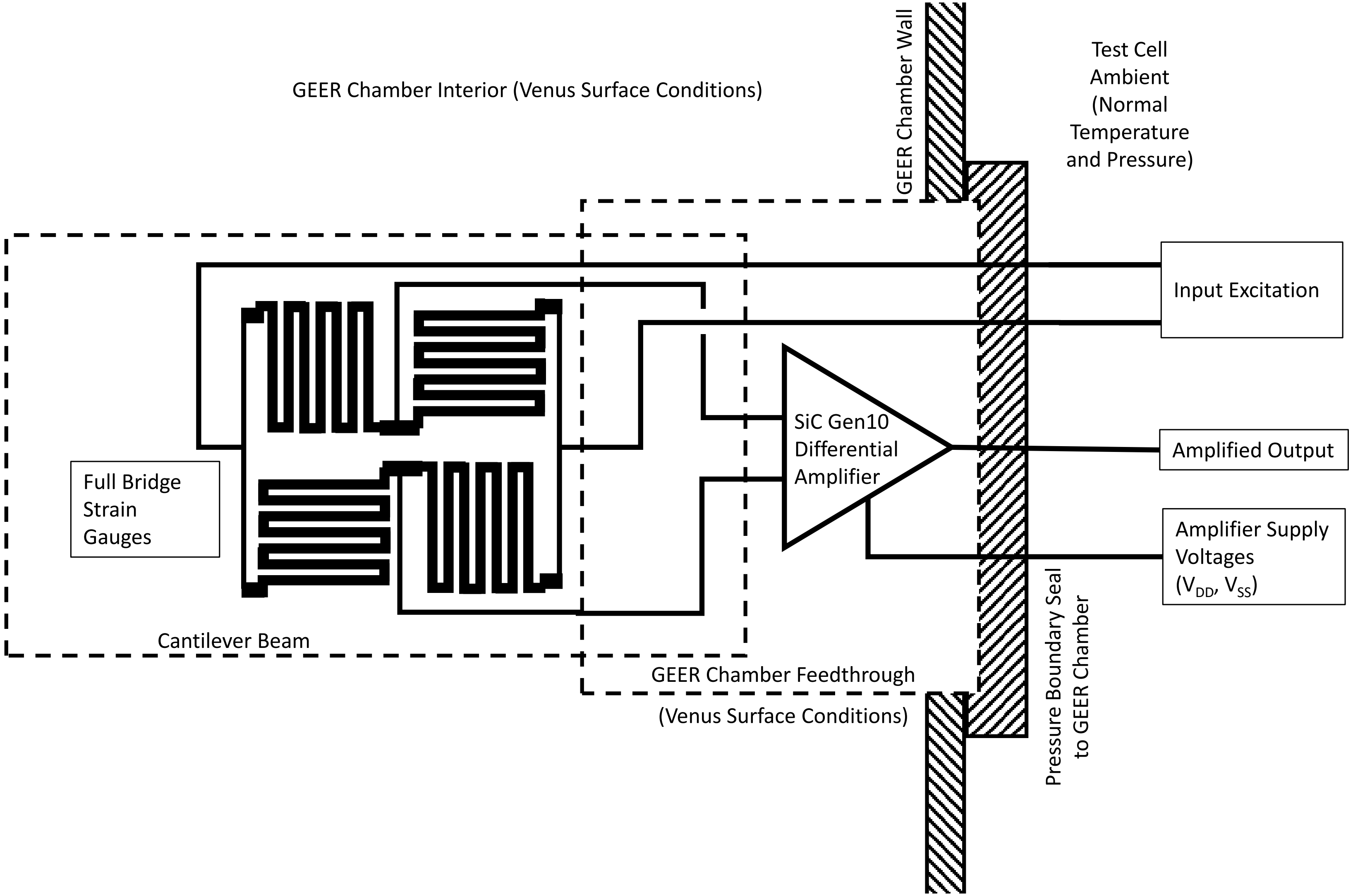


Development of a Venus Surface Wind Sensor

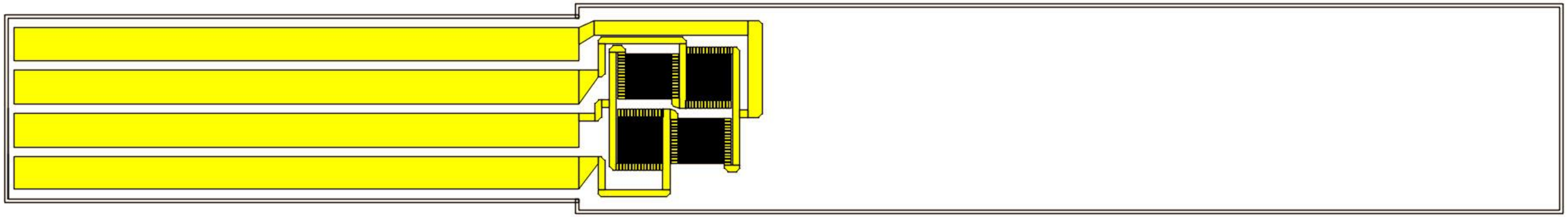
FABRICATION

Wind Sensor Probe Schematic

- Wind sensor probe designed to demonstrate the drag-force anemometer with electronics exposed together to the Venus surface environment



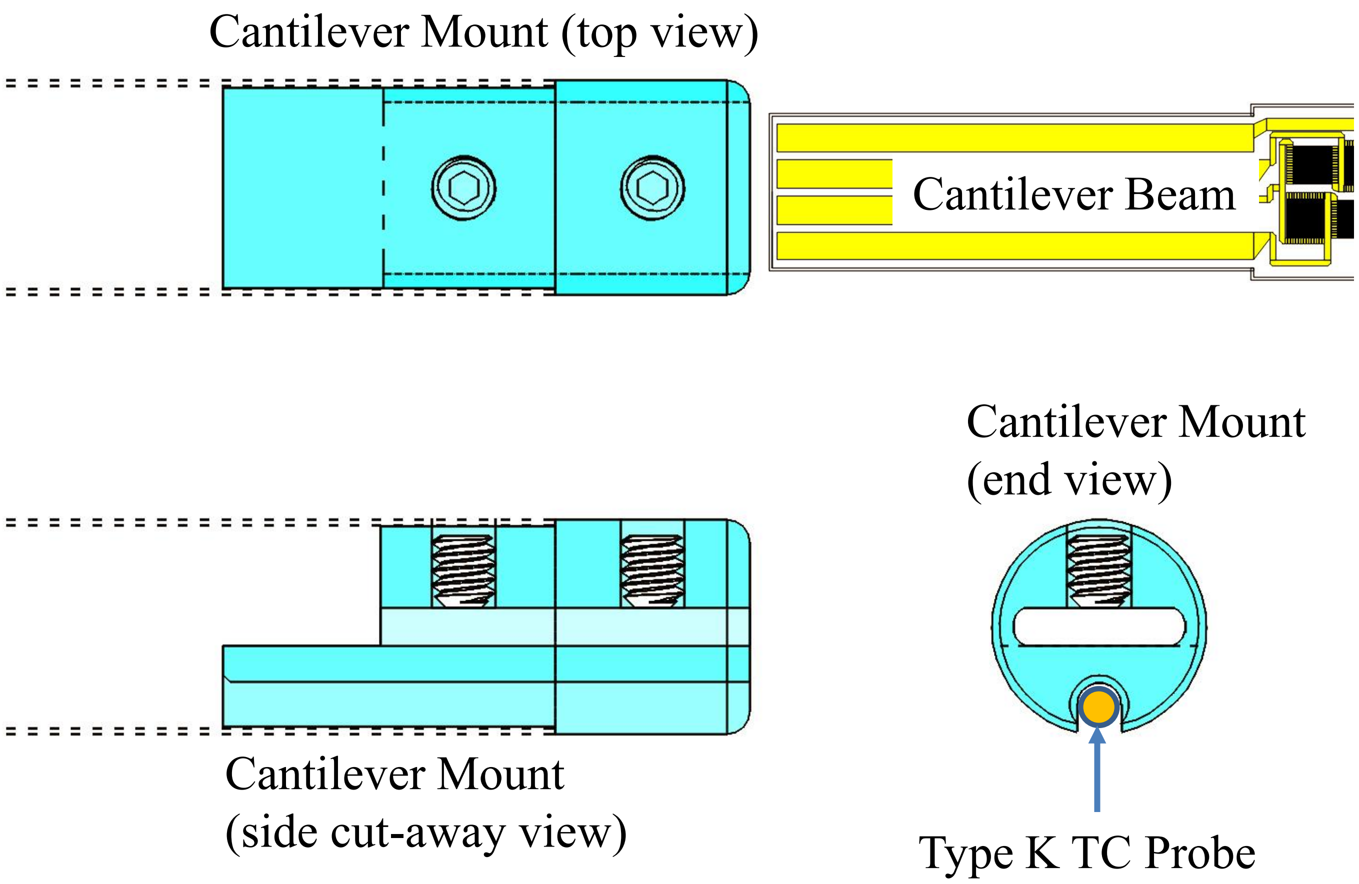
Cantilever Beam Fabrication



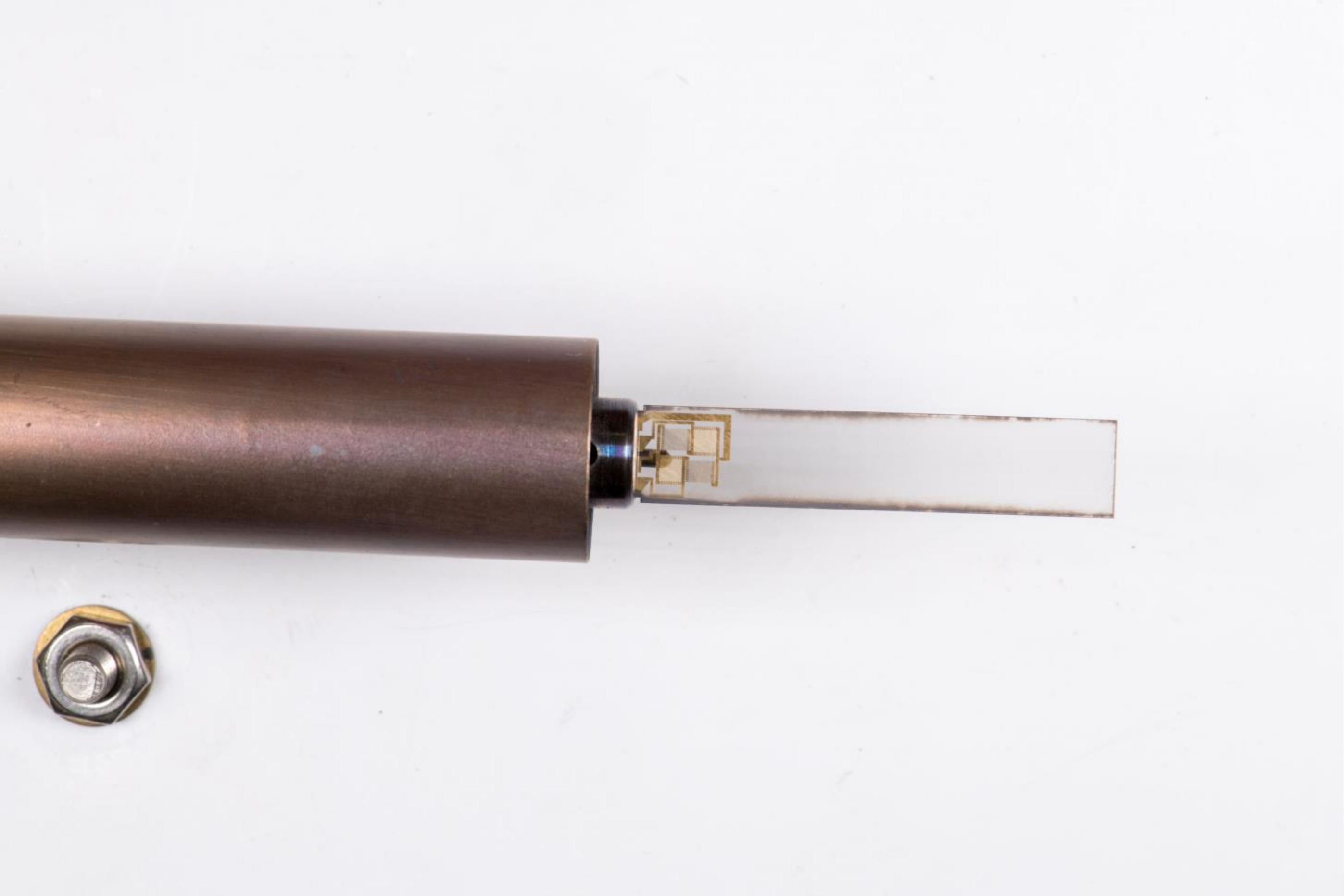
- Cantilever beams were fabricated from 127-µm-thick commercial sapphire wafers
- To form the strain gauge on the beam, the sapphire wafer was first coated with gold film using a titanium bond coat by sputtering in argon in a single run
- A lithographic pattern was then formed on the film with photoresist, and the uncovered metal film was etched away using aqua regia
- The photoresist was removed with acetone leaving the gold pattern, which was then annealed at 600 °C for 8 h in air using a box furnace
- Due to the microscopic voids in the sapphire wafer surface, a gold film of approximately 1 µm with a 50-nm titanium bond coat was found to be the ideal thickness to survive the annealing cycle
- After annealing, the cantilevers were laser cut from the sapphire wafer

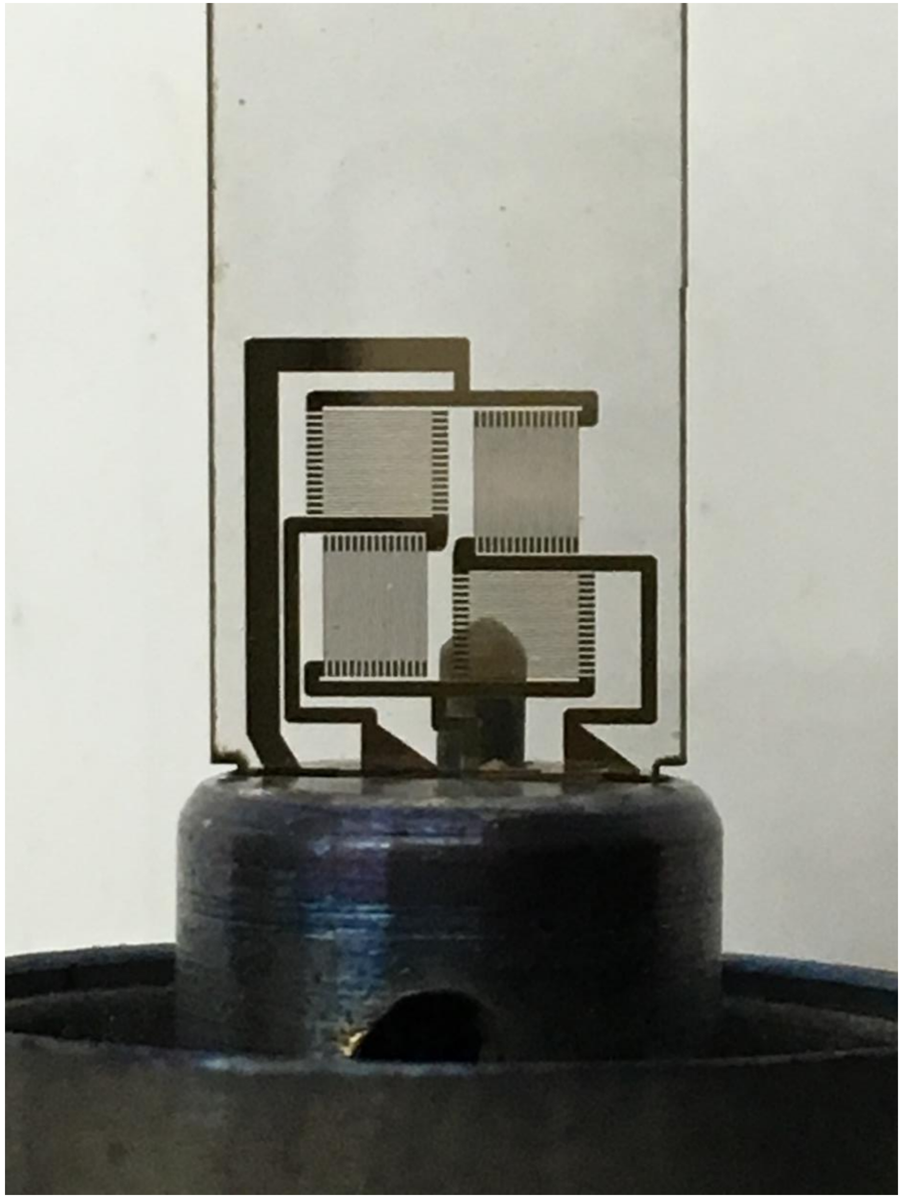
Cantilever Mount & Assembly

- A cantilever mount was custom made in-house from 316 SS to hold the beam in the ¾-in.-outside-diameter feedthrough for the test
- Gold wires of 0.010 in. diameter were attached to the cantilever beam with conductive paste, and then spot welded to the feedthrough wires
- A type K thermocouple (TC) probe was fixed in the cantilever mount below the beam to measure local gas temperature



Wind Sensor as Assembled





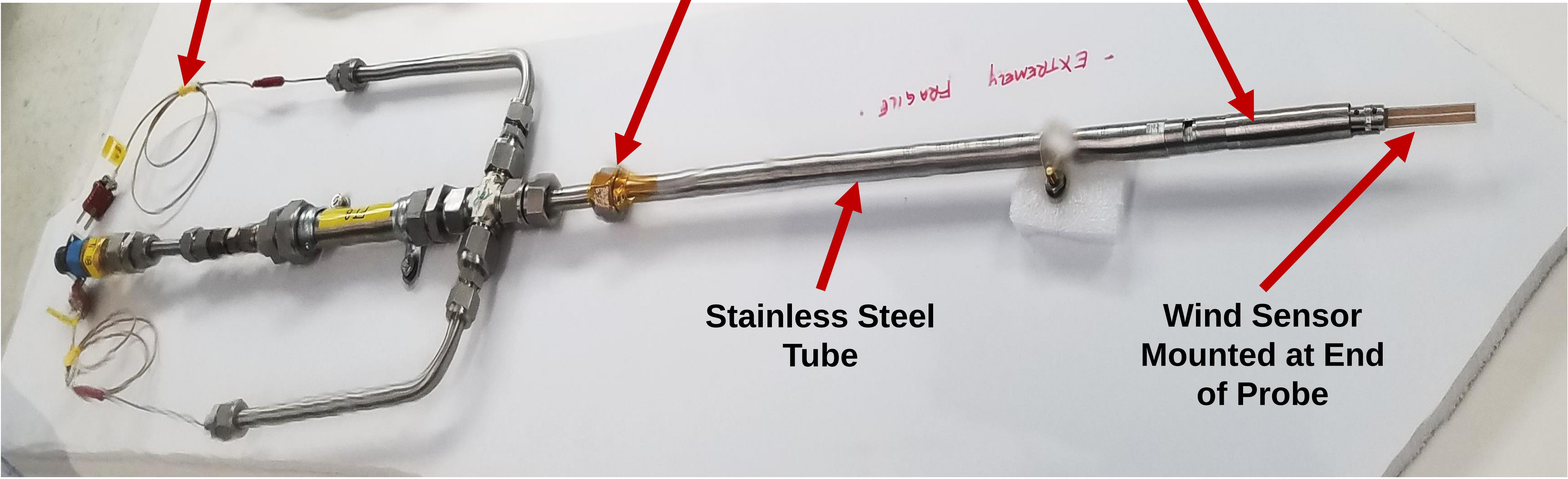
Feedthrough

- General feedthrough probe structure for insertion in the GEER chamber (earlier version)

Exterior Wire Interface Region

Pressure Boundary Seal to GEER Chamber

Location of SiC Amplifier in Tube



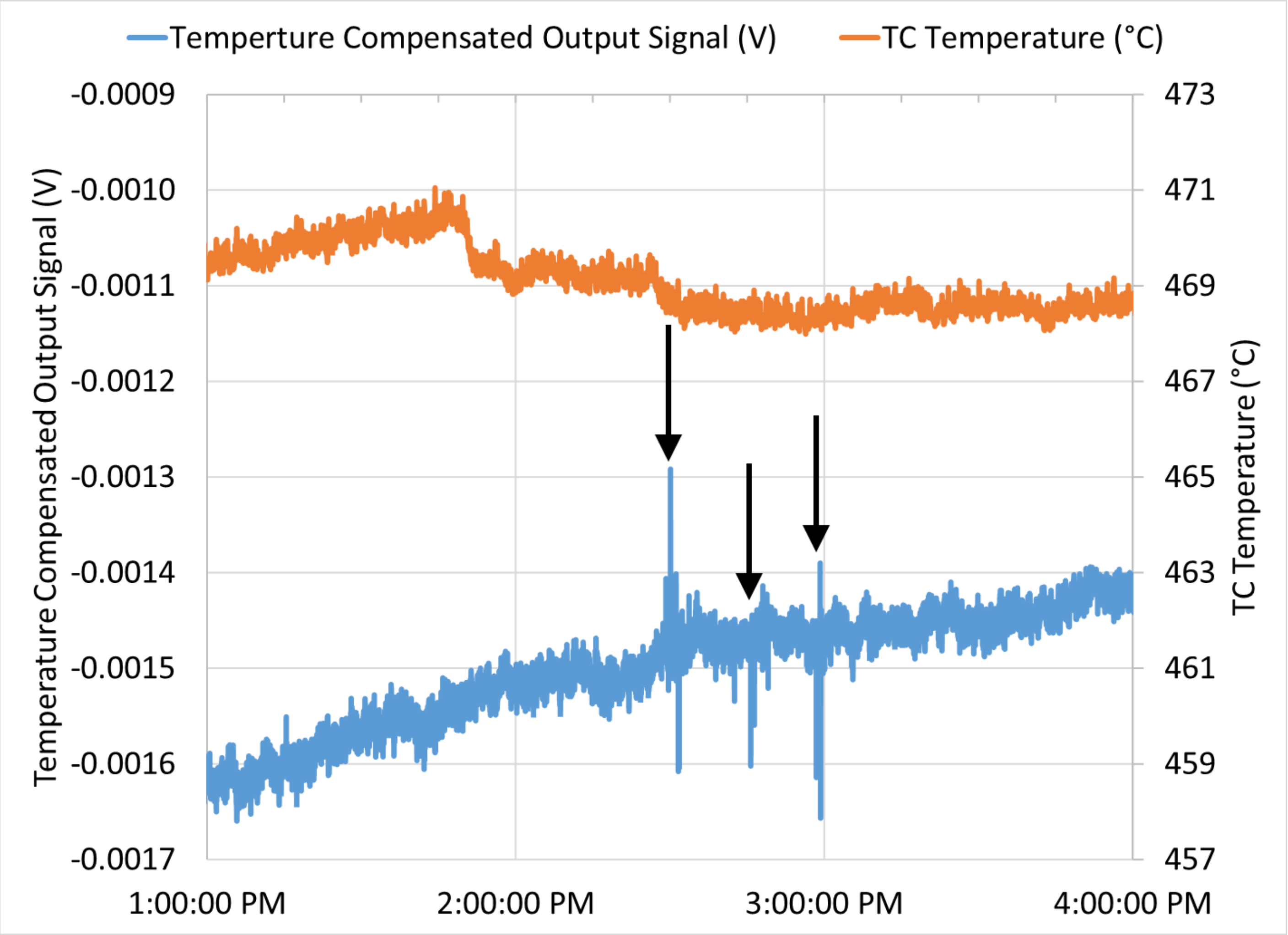
Installation in GEER Facility

Development of a Venus Surface Wind Sensor

RESULTS

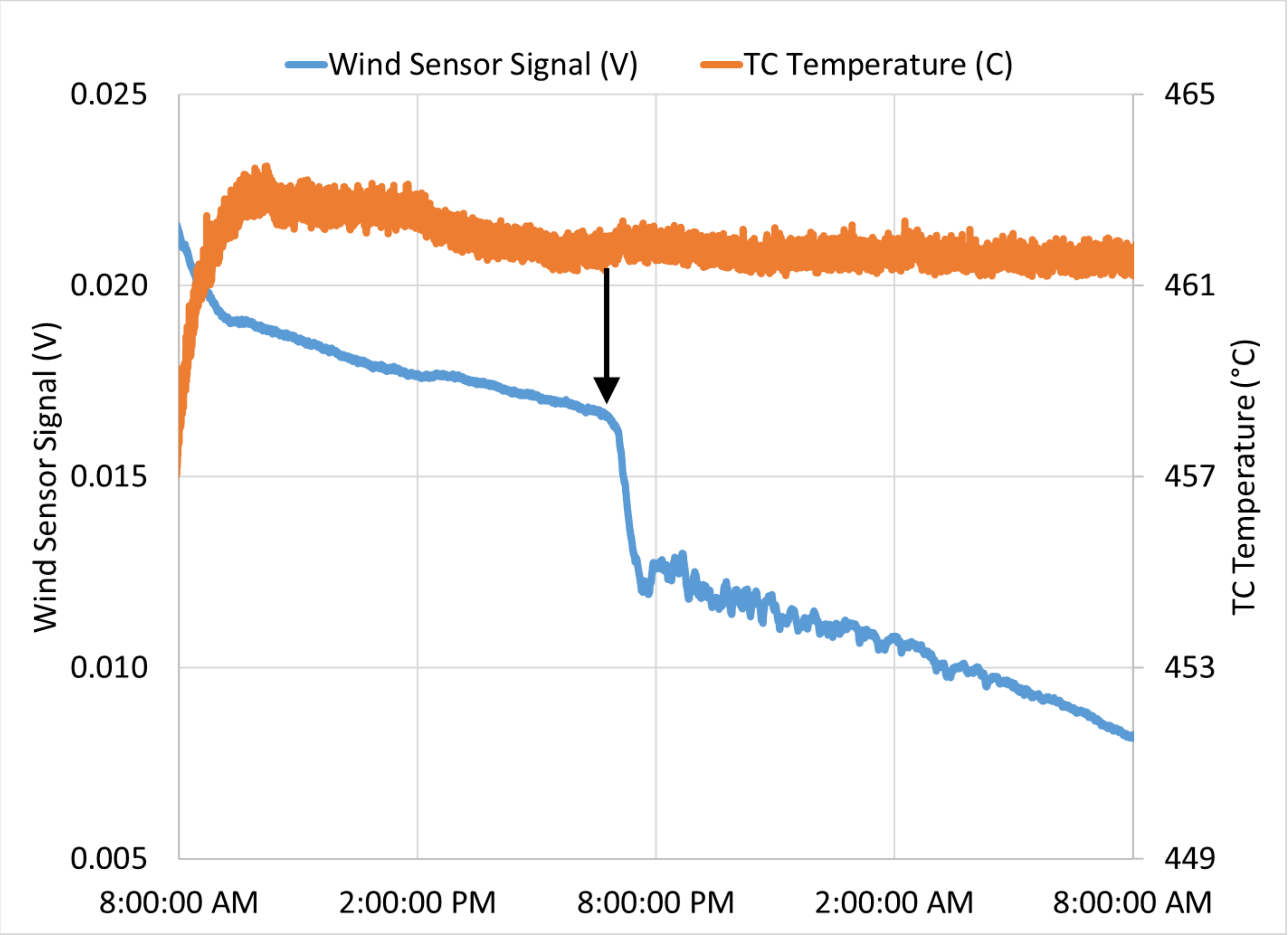
RFPT Run

- “RFPT” test 34-day duration
- Test conditions varying from Venus surface up to approximately 55 km elevation including ascent and descent
- Wind Sensor bridge input resistance of 38 Ω with 1 V excitation
- Data recorded every 2 seconds
- 45.2 µV/°C temperature dependence was determined from the vacuum data at 488 °C
- Sensor reacted to gas boosts not correlated to TC temperature



LFT1 Run

- "LFT1" test occurred over a total of 23 days at Venus surface conditions
- Internal chamber configuration different than RFPT Run
- New wind sensor cantilever beam with bridge input resistance of 65 Ω using 1 V excitation
- Sensor amplifier was not changed
- Data recorded every 2 seconds
- –90 µV/°C temperature dependence was observed for temperatures over 400 °C
- Sensor reacted to many gas boosts not correlated to TC temperature



Results

GEER run	RFPT	LFT1
Input resistance at 20 °C, Ω	37.9	65.3
Input resistance at Venus surface conditions (VSC), Ω	76.9	154
Power consumption at VSC (excluding amplifier), mW	13	6.5
Output ripple noise at VSC, mV	± 0.016	± 0.082
Maximum event signal, mV	0.18	5
Maximum signal-to-noise	11	61
Maximum strain, µm/m	0.14	4.0
Maximum estimated gust at VSC, m/s	0.094 ±0.011	0.495 ±0.055

Results

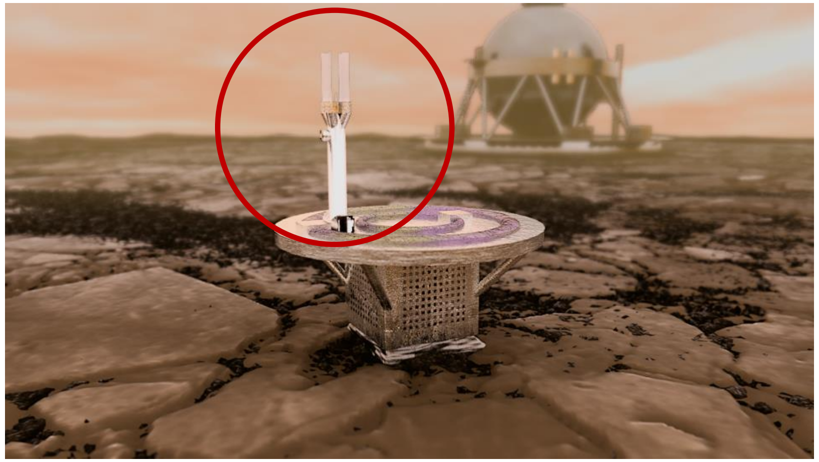
- Using the amplifier gain and gauge factor previously measured at VSC temperature, the estimated maximum gusts correspond to 0.094 and 0.495 m/s in the two runs, with ±0.010 and ±0.053 m/s uncertainties, respectfully
  - These values are within a lower range of wind velocities observed by Venera landers on the Venus surface.
- The maximum gusts correlated with gas boosts in the GEER chamber without corresponding temperature fluctuations recorded on the embedded TC
- The uncertainties of the velocity readings of the sensors are dominated by the uncertainty in the gauge factor
- The second iteration of the drag-force anemometer showed an improvement in signal-to-noise when boosts were registered
- Though the location of the wind sensors in the chamber were consistent for each run, the GEER chamber environment had some variation based on the articles under test inside the chamber and the actual run conditions. These variations led to changeability in the maximum wind gusts recorded by the sensors

Development of a Venus Surface Wind Sensor

CONCLUSIONS

Future Direction

- Future versions of the sensor design will include trim areas to produce sensors with strain gauges with more consistent resistances to further minimize variable temperature effects on the signal at VSC and maximize the overall sensitivity and output.
- Improvements in amplifier circuit characteristics are also expected in future generations of SiC amplifier integrated circuits.
- Operating the sensors in an array is the goal of the project for implementation on the Venus surface, and final configuration is yet to be established. The current concept is of a mast with three cantilever beams for x, y, and z sensitivity, each with their own operational amplifier.
- The results presented here suggest the strong viability of this concept towards reaching the goal of achieving long-term wind measurements on the Venus surface.



Summary

- NASA Glenn Research Center is developing a drag-force anemometer for use as a Venus surface wind sensor.
- The sensor uses technology proven in turbine-based applications and is designed for long-term stable operation in the Venus surface environment.
- Prototype drag-force anemometers were demonstrated with an integrated operational amplifier in Venus surface conditions (VSC), recording transient effects time-correlated to gas injection boosts in the GEER chamber.
- These prototype sensors are medium-fidelity systems built and operated to demonstrate overall performance in a simulated operational environment.
- To our knowledge, these results are the first demonstration of a wind sensor integrated with electronics operating in situ in simulated VSC.

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- Facilities: Microsystems Fabrication Laboratory, Glenn Extreme Environments Rig (GEER)

Reference:
John D. Wrbanek, Gustave C. Fralick, Gary W. Hunter, Roger Meredith, Mark Sprouse, Andrew Fausnaugh, LiangYu Chen, José Gonzalez and Kyle Phillips (2020) "Development of a Venus Surface Wind Sensor Based on a Miniature Drag-Force Anemometer" NASA/TM-20205007616