A Brief Overview of High Temperature Technologies for a Venus Long Lived Lander

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Lorain County Community College
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Outline

- Introduction
  - Venus Missions
  - Venus Studies
  - Technology Challenges
- Long Lived Platform Development
  - Electronics
  - Sensors
  - Communication
  - Power
- Summary and Future Prospects

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**.

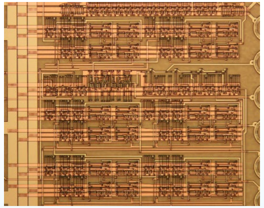
Core Capabilities (technical areas)

- 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

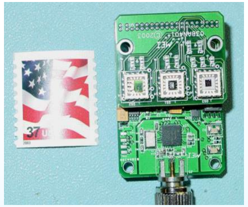
Microsystems Fabrication Facility

Facilities/Labs

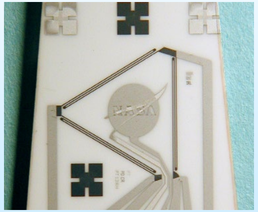
- Microsystems Fabrication Facilities
  - Class 100 Clean Room
  - Class 1000 Clean Room
- Chemical vapor deposition laboratories
- Chemical sensor testing laboratories
- Harsh environment laboratories
  - Nanostructure fabrication and analysis
  - Sensor and electronic device test and evaluation



SiC Signal Processing



Leak Detection Sensors

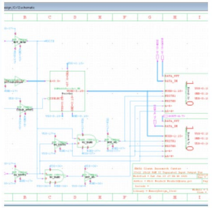


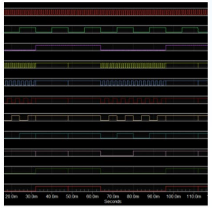
Thin Film Physical Sensors

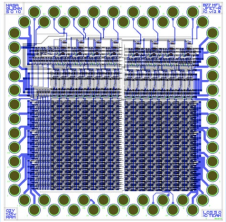
NASA Glenn Microsystems Fabrication Laboratory

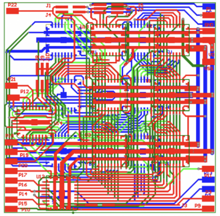
Vertically integrated design, prototyping, testing of extreme environment electronics & sensors

Design


Electrical Schematic Diagram of SiC Integrated Circuit

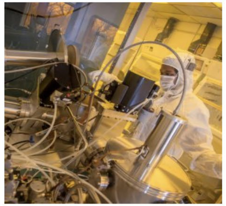

Electrical SPICE Circuit Simulation Waveforms of SiC Integrated Circuit


Mask Layout Design of SiC Integrated Circuit Chip


Design Layout of 4-level Multi-Chip Ceramic Circuit Board

Cleanroom Fabrication


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


Reactive Ion Etcher

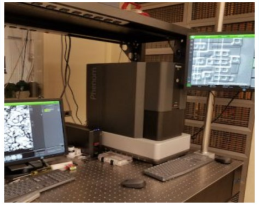

Rapid Thermal Annealer

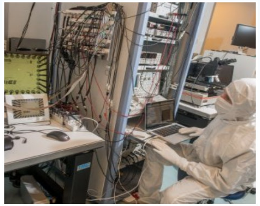

Wet Chemical Work Stations and Mask Aligner


Ultra High Vacuum Deposition System


Tantalum Silicide Sputter Deposition System

Test & Characterization


Scanning Electron Microscope with Energy Dispersive Spectroscopy


Electrical Probe Test Stations


High Temperature Ceramic Packaging Laboratory


Insertion of SiC Chip on Ceramic Board Into Oven

The only facility to have built and demonstrated long-lived 500º C semiconductor ICs

https://www1.grc.nasa.gov/facilities/microfab/

APPROACH

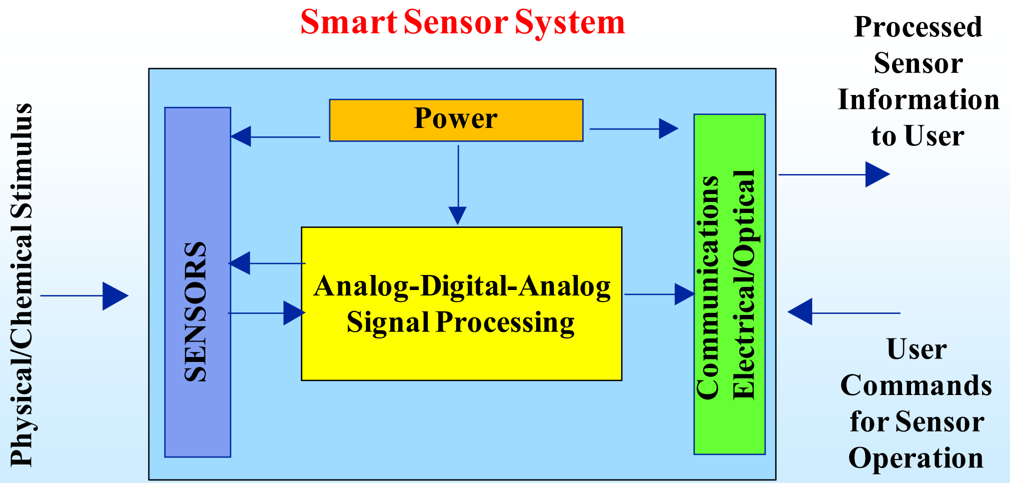
Interdisciplinary group of electronic engineers, chemists, materials engineers and physicists that can provide **Smart and Small Sensor Systems** to a broad range of aerospace applications.

- Using unique in-house capabilities, we produce ,cutting edge sensor system technologies that provide critical information (data), thus, enabling vastly improved decision-making capability, whether it be regarding designs, operations, the environment, or hazards.
- Our work, to quote Galileo, is to *"Measure what is measurable, and make measurable what is not so".*
- In this modern era, making a measurement does not just involve a sensor element (like a thermocouple), but rather a whole sensor system that provides:
  - ➢ Multiparameter information needed to understand the problem;
  - ➢ Local processing to optimize the quality and relevance of that information ;
  - ➢ Communication of that information in a manner that best fits the application; and
  - ➢ Tailoring of each integrated sensor system to meet the needs of the application.
- **We provide micro/nano-based tools and capabilities to enable:** Physical measurements; Chemical sensor platforms; High temperature electronic devices and communication, Harsh Environment Smart Sensors and Actuators and Integrated Sensor Systems

In this Information Age, our small, smart sensor system technologies are the enabling first step in acquiring information (data) about an aerospace system and/or an environment, leading to cognition and decision-making capabilities.

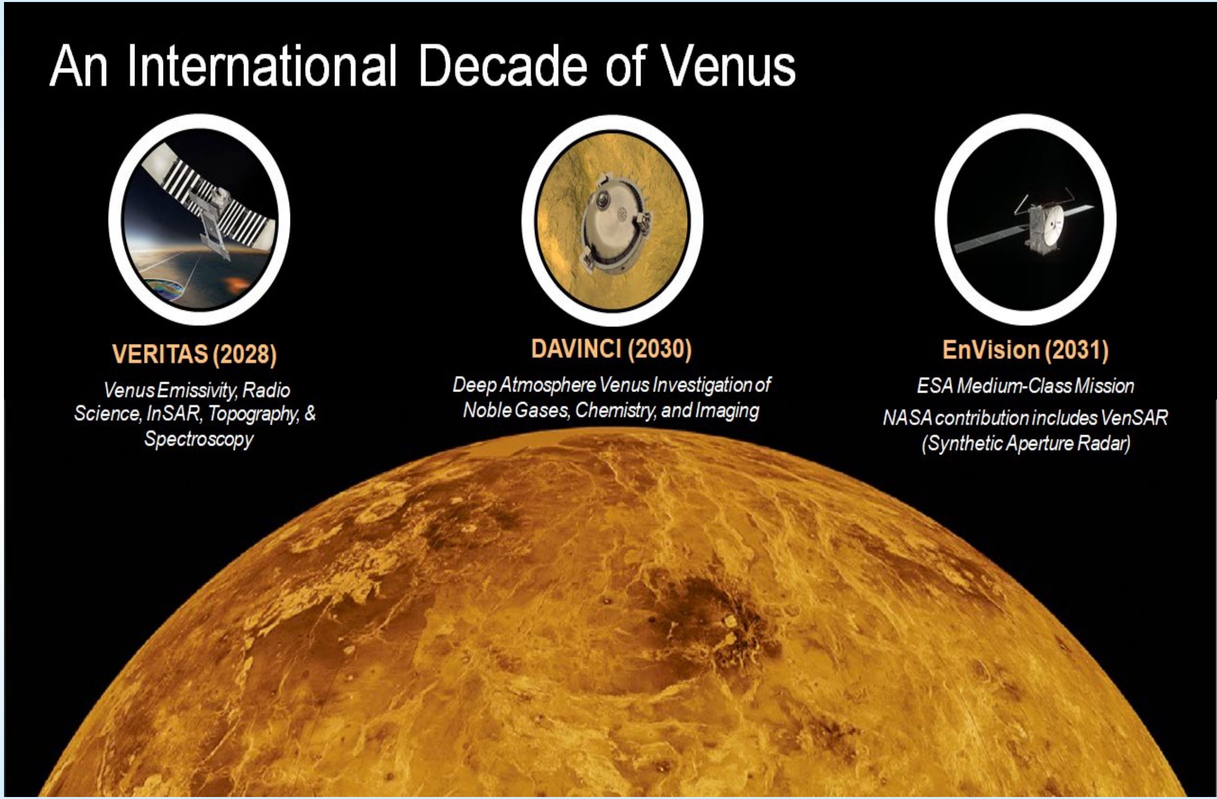
SMART SENSOR SYSTEMS BASED ON MICROSYSTEMS TECHNOLOGY

- A Range Of Sensor Systems Are Under Development Based On Microfabrication Techniques And Smart Sensor Technology
- Smart Sensor Systems Approach: Stand-alone, Complete Systems Including Sensors, Power, Communication, Signal Processing, And Actuation
- Microsystems Technology Moving Towards A Range Of Applications
- Enable System Level Intelligence By Driving Capabilities To The Local Level Using Distributed Smart Systems



Decade of Venus Exploration

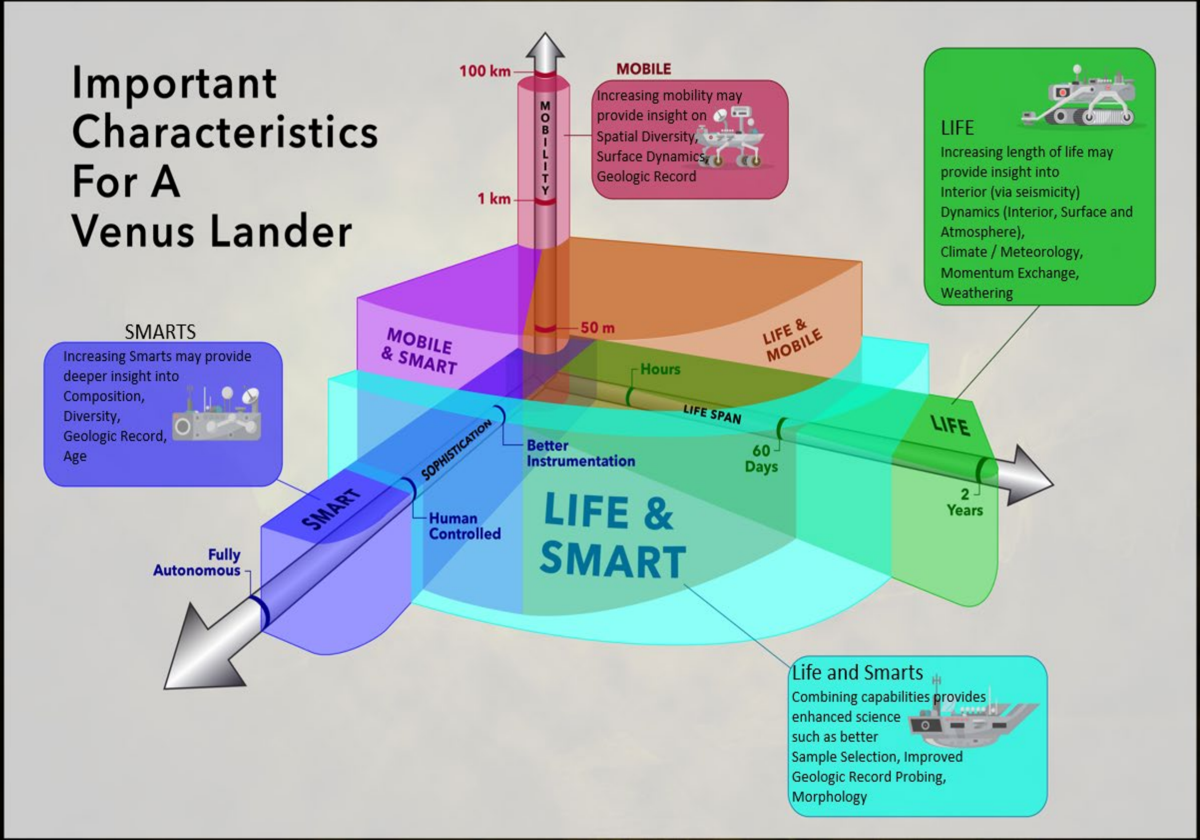
- Three Missions chosen for Venus Exploration in the next decade
- Two orbiters and one decent probe to explore Venus science
    - The DAVINCI+ probe descends to the surface but is not a lander mission
    - Development of one orbiter (VERITAS) presently delayed
- Extended duration surface measurements not addressed by these missions
- A number of science questions, e.g., seismology, are best addressed by in-situ measurements



L. Glaze, Venus Exploration Analysis Group Meeting, November 8–9, 2021
https://www.lpi.usra.edu/vexag/meetings/vexag-19/presentations/Glaze.pdf

Venus Surface Platform Study: Lander Characteristics
Leads: T. Kremic and M. Amato

https://www.lpi.usra.edu/vexag/documents/reports/Venus-Surface-Platform-Study-Final_11-4-21.pdf



Venus Surface Platform Study
Capability to Science Links

Capability to Science Links

Interior	Time	Smarts	Mobility	MSM
Structure	H			H
Composition	H	S		S
Dynamics	H			H
Heat Escape	S			S

Surface	Time	Smarts	Mobility	MSM
Composition		S		S
Dynamics (Eruptions, flows, …	H		H	
Diversity (Spacial)	H	S	H	S
Morphology	H	S	S	H
Age	S	H	S	S
Geologic Record (Layers, craters,..)	H	H	H	H

Interactions	Time	Smarts	Mobility	MSM
Gas and Surface Composition	H	H		H
Winds	H			H
Reactions	H	H		S
Momentum Exchange	H		S	H

An "H" in a field signifies that the capability is highly impactful in understanding that aspect of the science. A "S" in a field signifies somewhat impactful.

Technology To Capability Links

Technology	Capability		
	Time	Smarts	Mobility
Power (L – low, 10's of watts or less)	H	H	
Power (H - high, 100's of watts)			H
Cooling (Needs Power H)	S	H	
High Temp Electronics / Memory	H	H	H
Mechanisms (Drills, Wheels, …)	S	S	H
Autonomous Ops, Nav	S	H	H
SOA Instruments	H	H	H

An "H" in a field signifies that the capability is highly impactful in understanding that aspect of the science. A "S" in a field signifies somewhat impactful.

VEXAG Technology Plan 2019
Far-Term 2033 to 2042 : Venus Exploration More Like Other Planets, but Major Challenges

https://www.lpi.usra.edu/vexag/documents/reports/VEXAG_Venus_Techplan_2019.pdf

		Far-Term Missions						
	Mission Mode	**Advanced Orbiter /Smallsat Networks**	**Aerial Platforms Altitude Control**	**Lander - Cooled, Long Duration**	**Lander Network- Long Duration**	**Mobile Surface**	**Sample Return Clouds**	**Sample Return Surface**
System Technologies	Aerocapture							
	Entry							
	Descent and Deployment							
	Landing							
	Flight							
	Landers							
	Mobility							
	Ascent Vehicle							
	Small Platforms							
	Automation and Autonomy							
Subsystem Technologies	Energy Storage- Batteries							
	Energy Generation- Solar							
	Energy Generation - Radioisotope Power							
	Energy Generation-Alternative Sources							
	Thermal Control - Passive							
	Thermal Control - Active							
	High temperature mechanisms							
	Moderate temperature electronics							
	High temperature electronics							
	Communications							
	Guidance, Navigation, and Control							
Instrument	Remote Sensing - Active							
	Remote Sensing - Passive							
	In-Situ Aerial Platform and Probe							
	In Situ Surface - High Temperature Sensors							
	In Situ Surface - Long Duration Mobile Lab							

Challenges of Venus Surface Exploration

- 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
- Surface exploration of Venus for extended durations has notable science impact and is becoming more viable
- This presentation will provide a sampling of high temperature development and technologies that may have an impact on future Venus surface exploration

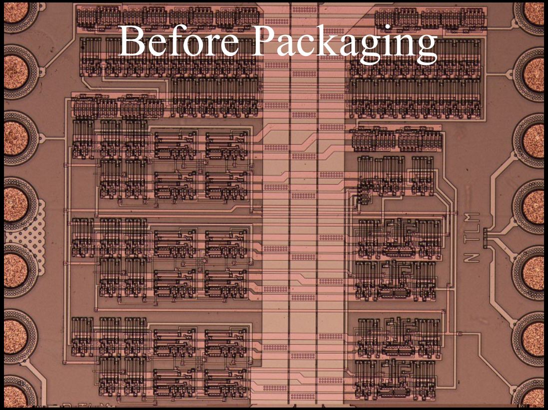
Surface Technology Development Overview

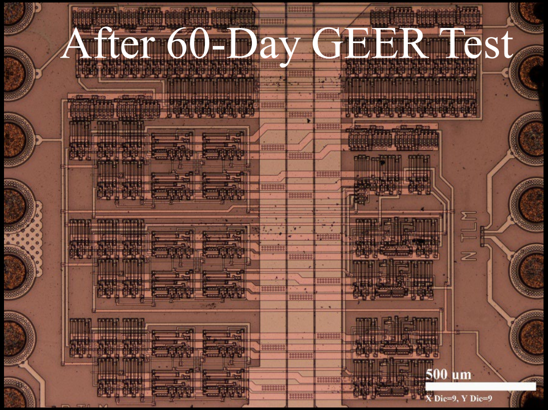
- Technologies relevant for Venus surface applications may often have their origin in other harsh environment applications e.g., aeronautics or industrial processing
- Material systems and engineering approaches standardly used for even harsh environment terrestrial applications may not be viable for 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)

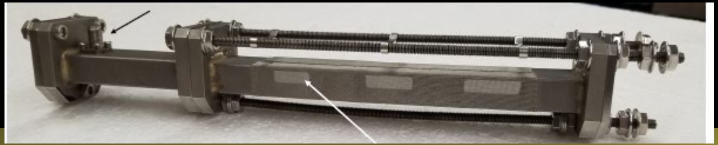
Material Choice (and GEER Testing) Matters

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 What Works in Venus Ambients

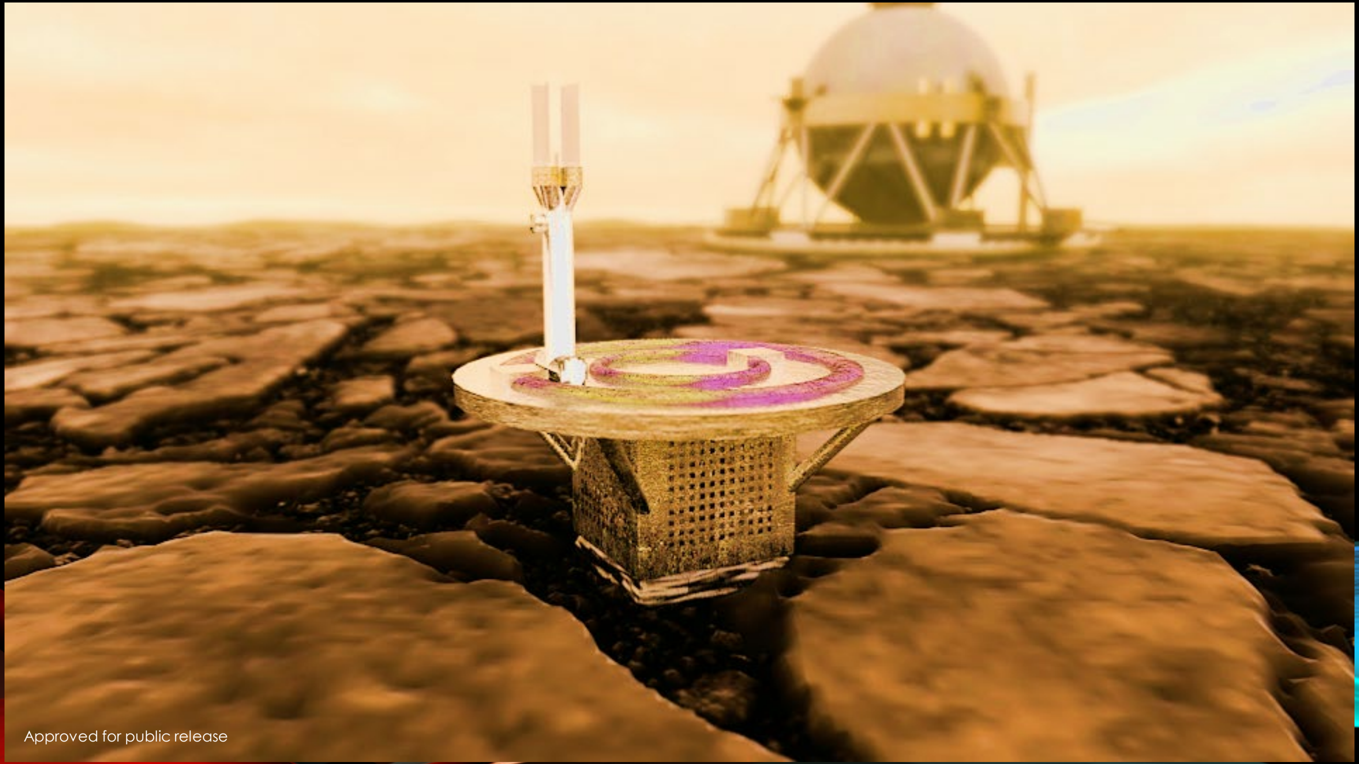
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2017EA000355

Tested Materials with Corresponding Outcomes		
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; Cl found 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
New Materials	Sputtered Aluminum	Reacts with HF to form AlF_3
	Titanium	Oxide on surface decreasing into bulk

Long Lived Surface Platforms Development

LONG-LIVED IN-SITU SOLAR SYSTEM EXPLORER (LLISSE)

PI TIBOR KREMIC, NASA GLENN



LONG-LIVED IN-SITU SOLAR SYSTEM EXPLORER (LLISSE)

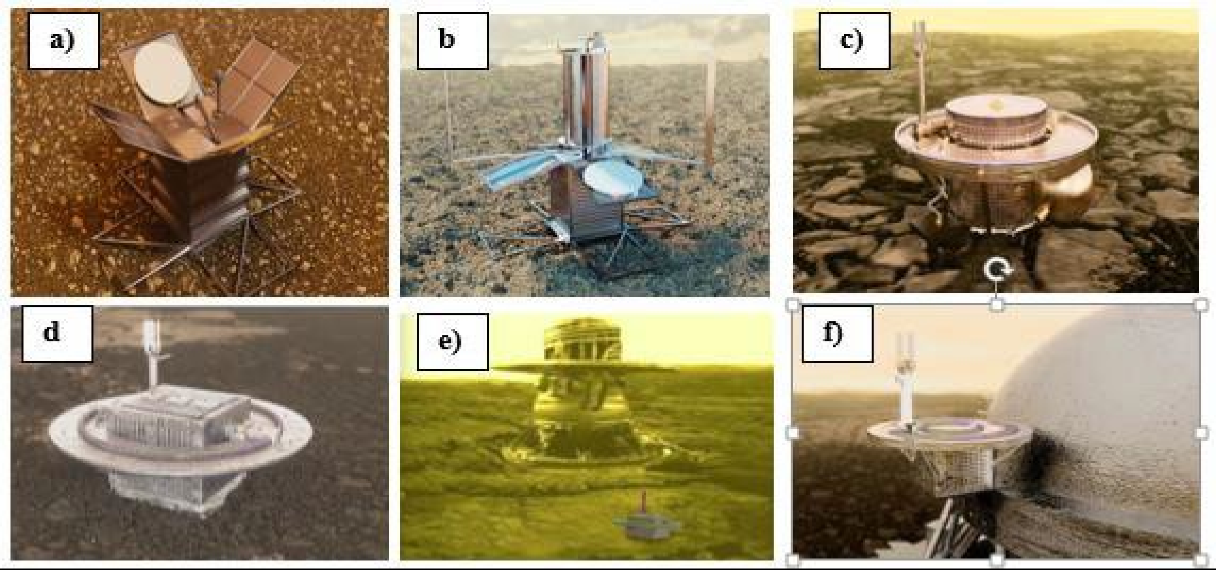
- LLISSE is a small and "independent" probe for Venus surface applications
- LLISSE acquires and transmits simple but important science
- Three key elements leveraged
  - Recent developments in high temperature electronics
  - Focused, low data volume measurements
  - Novel operations scheme

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

An Approach to achieve a class of long-lived landers for Venus

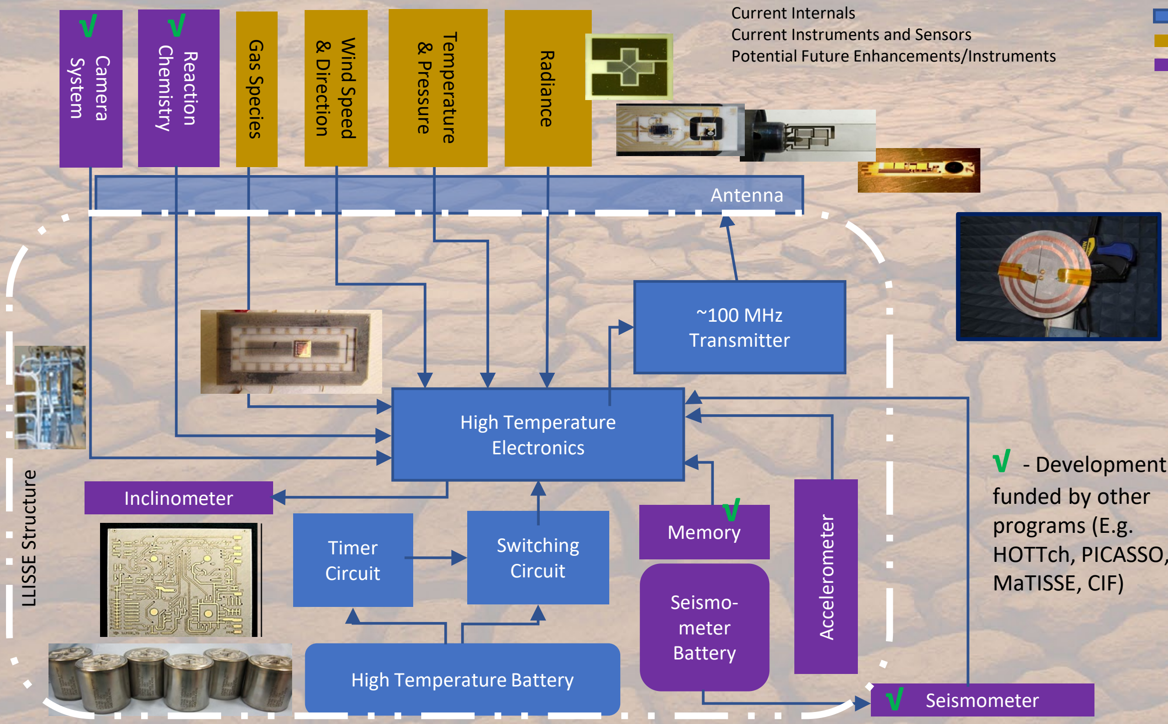


Artist's conceptions of the LLISSE platform and its various embodiments: a) Early concept for a battery-powered LLISSE after deployment; b) Wind-powered LLISSE after deployment; c) SAEVe lander; d) V-BOSS lander; e) Notional comparison of the V-BOSS lander to a Venera lander; f) A version of LLISSE mounted on a traditional, larger lander.

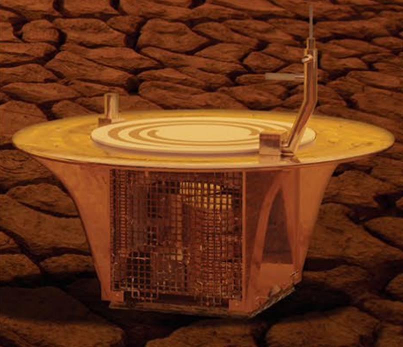
LLISSE Block Diagram

Legend

Current Internals
Current Instruments and Sensors
Potential Future Enhancements/Instruments



√ - Development funded by other programs (E.g. HOTTch, PICASSO, MaTISSE, CIF)



Approved for Public Release

HOTTech-21 Projects

Title	PI Information		
	First Name	Last Name	Organization
Venus Surface Solar Array	Joel	Schwartz	Jet Propulsion Laboratory
Non-Volatile, Low Power, and High Density SiC Memory For Future Venus Missions	Phil	Neudeck	NASA Glenn Research Center
High-Temperature MEMS based Venus Seismometer	Tibor	Kremic	NASA Glenn Research Center
High Temperature UV near field Imager	Emad	Andarawis	GE Research
A High Temperature Transmitter for Venus Surface Environment	Laurence	Sadwick	InnoSys, Inc.
Advanced Co-Based Nanocrystalline Soft Magnetics for Extreme Temperature Inductor Applications	Paul	Ohodnicki	University of Pittsburgh
A Venus Durable Actuator and Electronics System	Erik	Mumm	Honeybee Robotics Spacecraft Mechanisms Corporation

https://www1.grc.nasa.gov/space/pesto/space-vehicle-technologies-current/high-operating-temperature-technology-hottech/

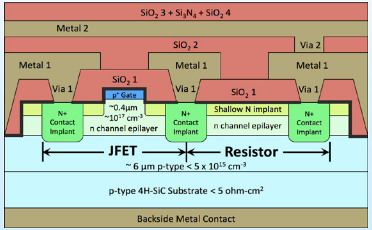
Electronics

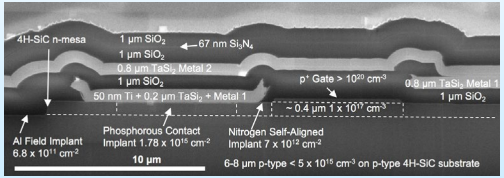
High Temperature Electronics Advancements

R&D 100 Award 2018

- *Unique capabilities have produced the World's First Microcircuits at moderate complexity (Medium Level Integration) that have the potential for long-lived operation at 500˚C*
- **Circuits contain 10's to ~1000 of Junction Field Effect Transistors (JFETs); An order of magnitude beyond a few JFETs previously demonstrated**
- **Enables a wide range of sensing and control applications *at High Temperatures***
    - **In-package signal conditioning for smart sensors**
    - **Signal amplification and local processing**
    - **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



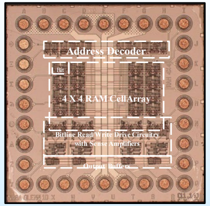


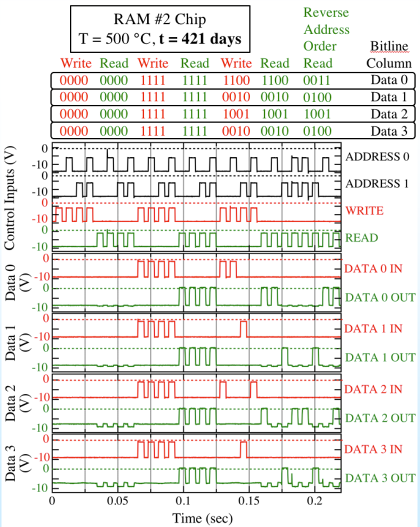
NASA GRC Electronics Development

2017 NASA Glenn SiC JFET IC "Version 10"
1+ year of operation in Earth air oven at 500 ° C Achieved

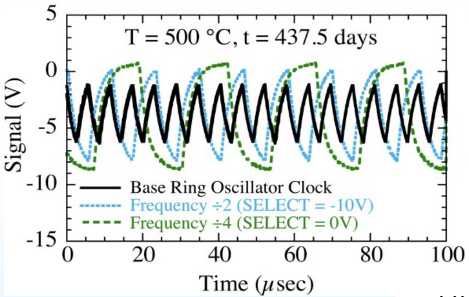
Version 10 ICs set high temperature durability world records in T ≥ 500 °C Earth-atmosphere oven testing.

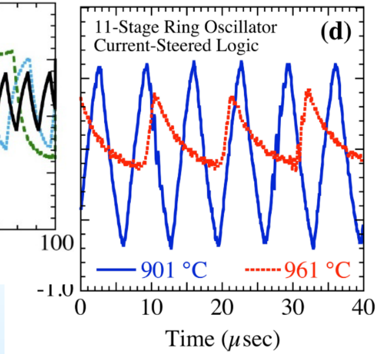
Complex ICs Operating more that 1 Year at 500 °C[1]

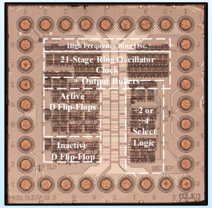




ICs Operating at World Record 961 °C[2]







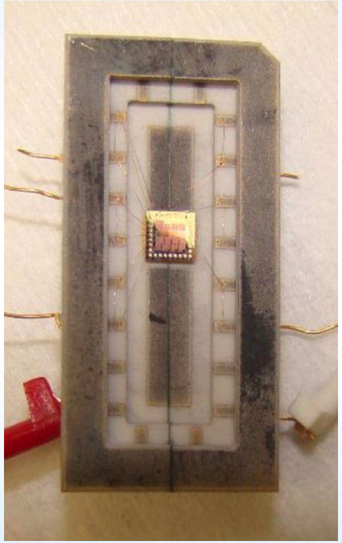
[1] 2018 Int. Conf. High Temperature Electronics p. 71
[2] IEEE Electron Device Letters vo. 38 p. 1082 (2017)

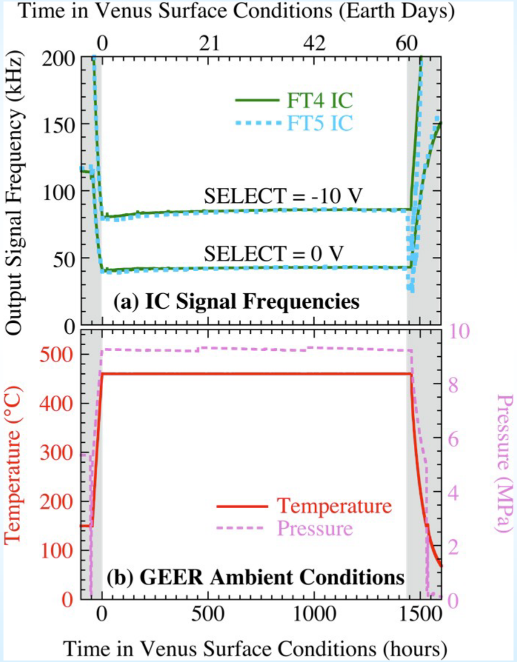
60-Day Venus Environment IC Test (in GEER)[1,2]

Two IC Version 10 ÷2/÷4 Clock ICs (175 JFETs/chip) successfully operated in GEER Venus surface conditions for 60 days duration.

Before GEER

After 60 days GEER





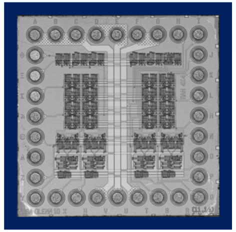
[1]Neudeck et al., IEEE J. Electron Devices Soc., vol. 1, p. 100 (2018).
[2]Chen et al., Proc. 2018 Int. High Temperature Electronics Conf.

NASA Glenn SiC JFET IC Technology Progress

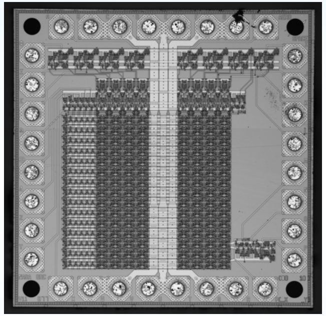
"Learn by doing" fabricating and testing **successive upscaled generations** of prototype IC wafers/chips

See P. Neudeck Presentation For Latest Results

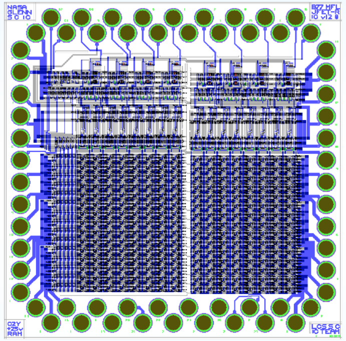
"IC Gen. 10" (2017)
(16-bit RAM, 195 SiC JFETs)
2 prototype 75 mm diameter SiC epi-wafers
6 μm gate length, 6 μm resistor width
3 mm x 3 mm, 32 I/O Bond Pads



"IC Gen. 11" (2018)
(120-bit RAM, ~ 1000 SiC JFETs)
4 prototype 75 mm diameter SiC epi-wafers
6 μm gate length, 3 μm resistor width
4.65 mm x 4.65 mm, 32 I/O Bond Pads



"IC Gen. 12"
(248-bit RAM, ~ 2000 SiC JFETs)
6 prototype 100 mm diameter SiC epi-wafers
3 μm gate length, 2 μm resistor width
5 mm x 5 mm, 62 I/O Bond Pads



Key IC Version 10 Accomplishments*

- **400+ days stable 500 °C electrical operation**
- **60 days stable Venus surface environment electrical operation**
- 961 °C electrical operation (short-term)
- -190 °C cryogenic electrical operation
- Radiation immunity through 7 Mrad(Si) ionizing dose and 86 MeV-cm^2/mg heavy ions (25 °C)

Key IC Version 11 Accomplishments

- **5-fold reduction in logic gate power**
- **First ICs designed for LLISSE**
- 500 °C 8-bit Analog to Digital converter
- Few days 500 °C ~1 kbit ROM operation

Wafer fabrication in progress

*Published results, see https://www1.grc.nasa.gov/research-and-engineering/silicon-carbide-electronics-and-sensors/technical-publications/

Example Sensors/Instruments

LLISSE Chemical Sensors Status
Chemical Sensors Summary

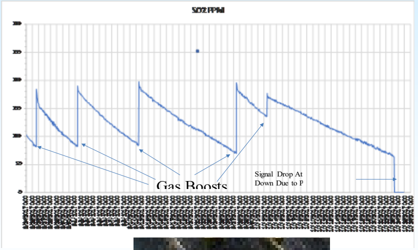
Background: ***Sensor Array Developed Under Completed NASA Phase I and Phase II SBIR***

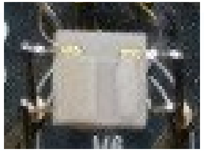
- ➢ Demonstrated Measurement of Key Species Including SO_2, H_2O, OCS, CO, HCl, and HF Under Relevant Conditions
- ➢ Sensors are selective to targeted species with minimal cross sensitivity to other species in Venus atmosphere

Current Status:

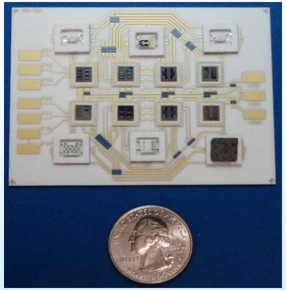
- Development of Chemical Sensors (including GRC sensors) Integrated with NASA GRC SiC Electronics On-Going in HOTTech project
  - ➢ Four Chemical Microsensors (SO_2, CO, OCS, HF) Tested for 60 days in Venus Simulated Conditions in GEER
    - All 4 Sensors Operated Nominally During 60 Day Test
    - First Demonstration of In-Situ SO_2 Tracking in GEER for Extended Periods
  - ➢ HF Sensor Integrated With Signal Transduction/Amplification SiC Electronics Monitored HF Boosts in GEER 10 Day Test
- Permanent installation as a monitoring system in GEER planned
- Modules being developed for measurement of volcanic gas emissions (SOx, CO, OCS, H_2O, NO, HF) using high temperature gas sensors and GEN-12A chemical sensor ASIC (single chip with all functions) near fissure/vent.

SO_2 Sensor Operation in GEER for 60 Days in Venus Simulated Conditions



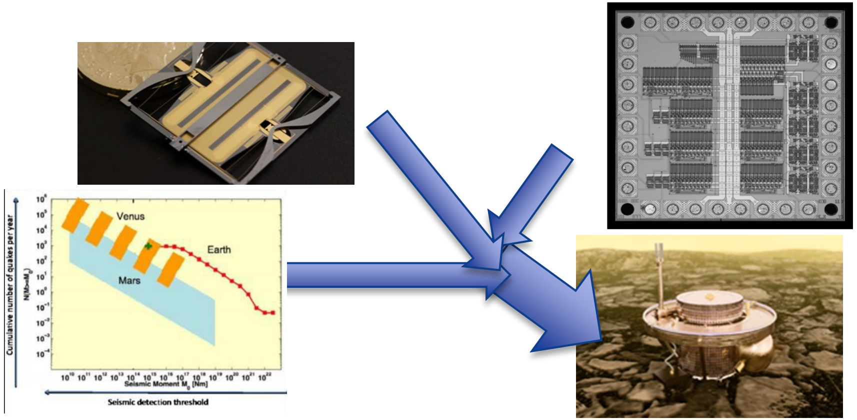


SO_2 MicroSensor



Compact “Credit Card” Format Board Single Sided

High-Temperature MEMS based seismometer



Team Member(s)/Institution(s)

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Technology Overview/Description

<u>Overall objective:</u>

Leverage existing MEMS seismic sensor, recent developments in high-temperature electronics and sensors, terrestrial analogues and Venus seismicity studies, and an expert team to design and mature a MEMS based seismometer suitable for use on long-duration Venus landers, like SAEVe.

Accomplishing this involves:

- Assessing / modifying existing MEMS seismic sensors that may be suitable for Venus applications
- Developing driving/interfacing electronics to support required operations and interfaces of a notional lander
- Design and fabricate a 1-axis instrument (but readily scalable to 3 axis) and verify performance via tests and analysis. Iterate.
- Mature instrument and demonstrate performance of breadboard system in Venus surface conditions against model-based predictions and reach a TRL of 4 or greater

Technology Goals

1. Develop science-based requirements for a Venus seismometer that consider the Venus unique operations circumstances
2. Assess MEMS seismic sensors, modify as required, and fabricate and test under Venus conditions
3. Analysis and the sensor / electronics system and design, fabricate and test a 1 axis system that meets requirements and is consistent with expected Venus mission applications
4. Demonstrate operations of breadboard 1 axis instrument in Venus conditions

Starting TRL: 2 **Ending TRL: 4**

Communications

LLISSE Communications Summary

History of Cutting Edge Development in High Temperature Wireless Communications

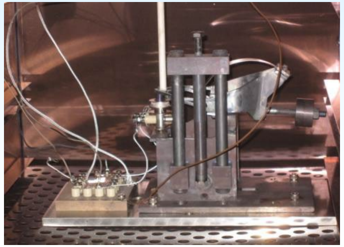
- Wireless Signal Spectra For High Temperature Seismometer Sensor Displacements Demonstrated (2012)
- Demonstrated Wireless Pressure Sensor At 475ºC Including Pressure Sensor, SiC Circuitry, and Wireless Circuit (2013)

Development Approach

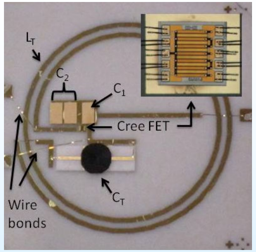
- Activities Include Venus Relevant Development Of Antennas, Transmitters, and Other Components
- Increasing Capabilities and Complexity of High Temperature Electronics Circuits Increases Communication System Capabilities
- Targeted Operation of Communication System from 100 to 150 MHz.

Status

- Development of Circuit Hardware Architecture for Higher Frequency Communications Systems On-going
- Baseline LLISSE Antenna Materials and Design Approach Identified And Initial Material Testing In Venus Simulated Conditions Begun
- Proof-of-concept Demonstration of Ability to Determine Orientation of the Lander from the Communication System Achieved
- Propagation studies conducted in GEER at higher frequencies; transmission with limited losses observed.



Wireless seismometer and circuit in an oven at 500ºC

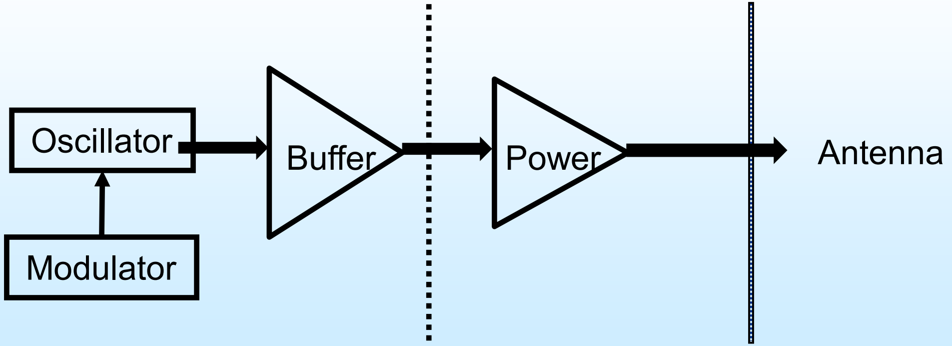


Wireless Pressure Sensing Circuit

LLISSE Communications Status

Baseline Communications Approach

- Communications System Includes: Active Circuits, Passives, Antenna
- Targeted 100 MHz Frequency Range; Relevant for Venus Surface Operations
- Communication System Dependent on SiC Circuit Advancements
  - First SiC-based Communication Circuit Designed To Operate On A Long-lived Venus Lander Based on SiC JFET technology Demonstrated
- Final Communications System at 100 MHz Will Be Based on BJT (Not JFET) Transistors
- Antenna Materials Must Be Both Resilient to Venus Surface Conditions and Have High Permittivity



Physical Layer Communications Technologies: Harsh Planetary Environments, IEEE Microwave Magazine, Volume 22, Issue12: https://ieeexplore.ieee.org/document/9597601

Power

LLISSE Power

Performance Summary

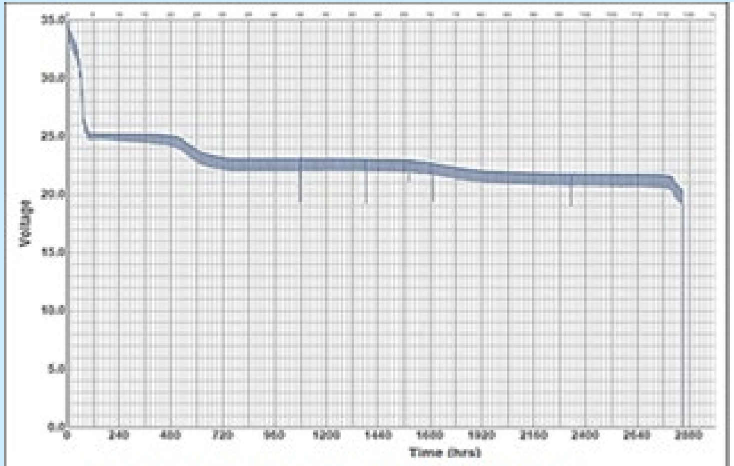
Voltage (max./min.): +25 V/ 0.0/-25 V

Current: 0.2 with pulses up to 12A

Life: 60 Earth days

Temperature: + 465°C

Environment: Venus Surface @ 93 Bar

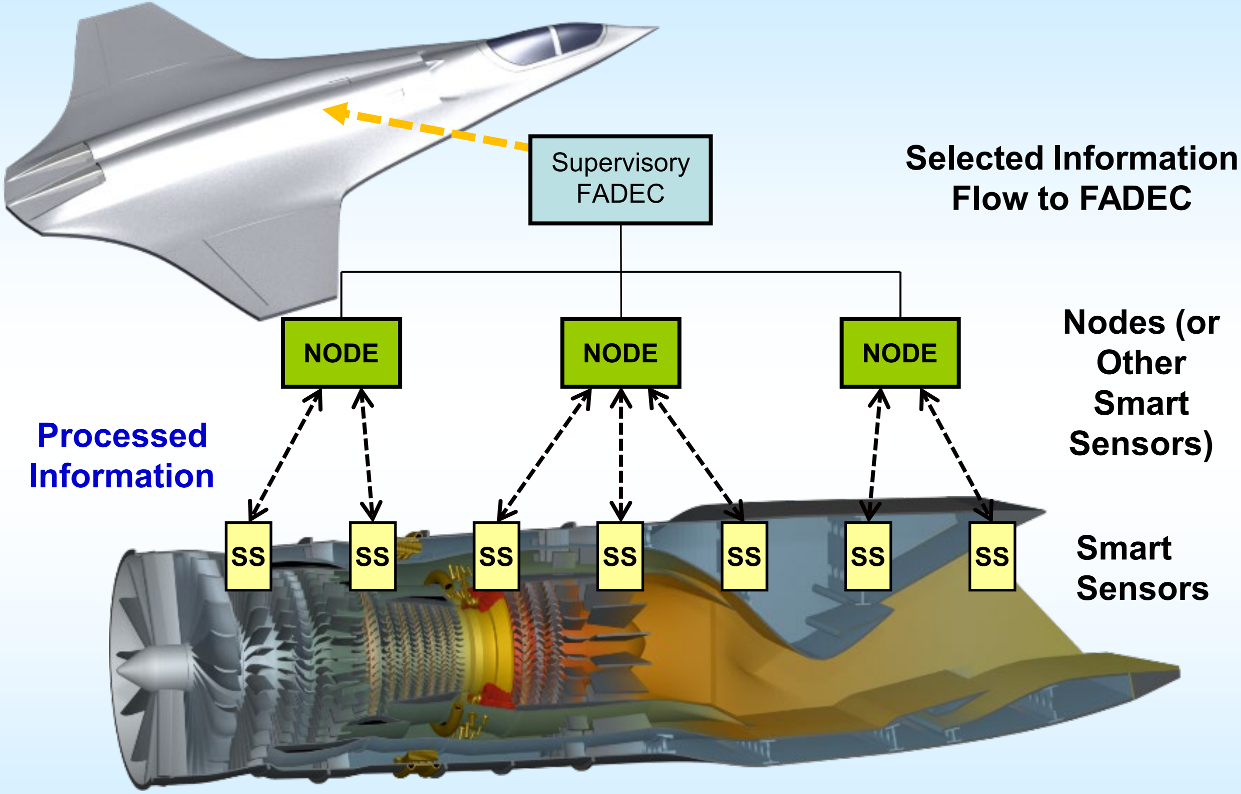


A 17 cell battery operating for 118 days at Venus temperatures; initially it was not certain it could be done, and now it's been demonstrated.

Current Status

- Battery chemistry demonstrated for 118 days at Venus temperatures
- Currently performing sensitivity experiments to optimize battery packaging and mass for a flight-like 60-day battery.
- Trading packing options to maximize robustness to off-nominal impacts, orientation, and operations.
- Developing detailed mission driven scenarios to completed testing and verification plans for TRL-6.

Broad Use Technology
Implementation of Distributed Engine Controls with Smart Wireless Sensors



Hunter, G. W. and Behbahani, A. "A Brief Review of the Need for Robust Smart Wireless Sensor Systems for Future Propulsion Systems, Distributed Engine Controls, and Propulsion Health Management", Proceeding of the 58th International Instrumentation Symposium, Hyatt Regency La Jolla, San Diego, California, 4–7 June 2012

SUMMARY AND FUTURE PROPECTS

- **Venus Exploration Has Returned With Missions Planned In The Next Decade; Surface Exploration Not Presently Addressed**
- **Venus Surface Exploration Has Unique Technical Challenges Due To The Extreme Environment**
- **Venus Technology Plan: More complex missions are envisioned as a range of technologies mature**
- **The Combination of Smarts, Mobility, and Extended Life is Enabling for Surface Lander Platforms Impacting Both Science and Capabilities**
- **A Range Of Harsh Environment Technologies Are In Development To Enable Long Life Surface Missions in e.g., LLISSE and HOTTech**
  - **Electronics**
  - **Sensors/Instruments**
  - **Communications**
  - **Power**
  - **Actuation**
- **Recent Advances Have Been Significant And The Prospect Of Long-lived Missions On The Venus Surface Is Becoming Increasingly Viable**

Backup

Venus Technolgy Plan Team Members

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Technology Framework

	Technology Area	Time Frame	Assessment
System Technologies	Aerobraking	N, M	Aerobraking is a mature technology and autonomous aerobraking can reduce the cost and risk while improve the time to achieve the desired orbit.
	Aerocapture	N, M	A large gap in aerocapture has been met with a nearly mature HEEET technology. ADEPT with a sounding rocket sub-orbital flight test requires minimal additional development for enabling small and cube-sat missions to Venus.
	Entry (Upper Atmosphere)	N,M	ADEPT with a sounding rocket sub-orbital flight test requires minimal additional development for enabling small and cube-sat missions to Venus.
	Descent and Deployment	M,F	Control descent of probes, drop-sondes, and aerial platforms in development for future use in atmospheric profiling. Incorporating guidance, with improved navigation, could enable more accurate targeting for these systems.
	Entry, Descent, and Landing (EDL) Modeling & Simulation	N,M, F	Updates are needed for multiple modeling systems, including modeling for descent GNC pin-point landing and hazard avoidance.
	Aerial Platforms	N,M, F	Technology for near-term missions is mature. Technology investments are needed including new science instrumentation and modeling tools to characterize the behavior of vehicles in the Venus environment. However, there are no technological show stoppers to impede the development of these capabilities.
	Landed Platforms	N,M,F	Three classes of landed platform will be needed of increasing technical challenge: short duration containing analytical instruments (near term, current technology), long duration with sensors (mid term) and long durations with a complex instrument suite (far term). Significant advances have been made to enable longer term surface platforms.
	Mobile Platforms	F	Mobile systems would require a range of subsystems technology to allow, e.g., motion, power, cooling, and actuation, for extended periods. These are major challenges for mobile systems on the surface, but achieving these objectives with floating platforms may be more viable but also challenging.
	Ascent Vehicles	F	Ascent vehicles are only needed for Venus sample return. This is a very immature technology and much more demanding than for Mars surface sample return. Some concepts for Venus Surface sample return require the Venus Ascent Vehicle to descend to the surface. Atmospheric return missions are more feasible but significant challenges remain.
	Small Platfroms	N, M, F	SmallSat, CubeSat and other small platform technology can make important contributions to Venus exploration. The development of small platform concepts as an addition to larger missions, as well as a new mission type or mission augmentation, is an integral part of a complete multistage Venus exploration program.
	Automation and Autonomy	M, F	Increasing capabilities for automation and autonomous decision-making combined with increasing computing power can change the way missions are conducted. Efforts to transition automation and autonomous technologies to Venus specific applications would enhance science delivered and mission success.

VEXAG Technology Plan 2019
Mid-Term 2023 to 2032: From This Baseline, New Missions and Science in Next Decadal Period

		Mid-Term Missions					
	Mission Mode	Advanced Orbiters	Subsatellite/ Small Sat Platforms	Multiple Deep Probes and Sondes	Increased Duration Large Lander	Small Platform Lander- Long	Aerial Platforms Altitude. Control Upper and Mid Cloud
System Technologies	Aerocapture						
	Entry						
	Descent and Deployment						
	Landing						
	Flight						
	Landers						
	Mobility						
	Ascent Vehicle						
	Small Platforms						
	Automation and Autonomy						
Subsystem Technologies	Energy Storage- Batteries						
	Energy Generation- Solar						
	Energy Generation - Radioisotope Power						
	Energy Generation-Alternative Sources						
	Thermal Control - Passive						
	Thermal Control - Active						
	High temperature mechanisms						
	Moderate temperature electronics						
	High temperature electronics						
	Communications						
	Guidance, Navigation, and Control						
Instrument	Remote Sensing - Active						
	Remote Sensing - Passive						
	In-Situ Aerial Platform and Probe						
	In Situ Surface - High Temperature Sensors						
	In Situ Surface - Long Duration Mobile Lab						

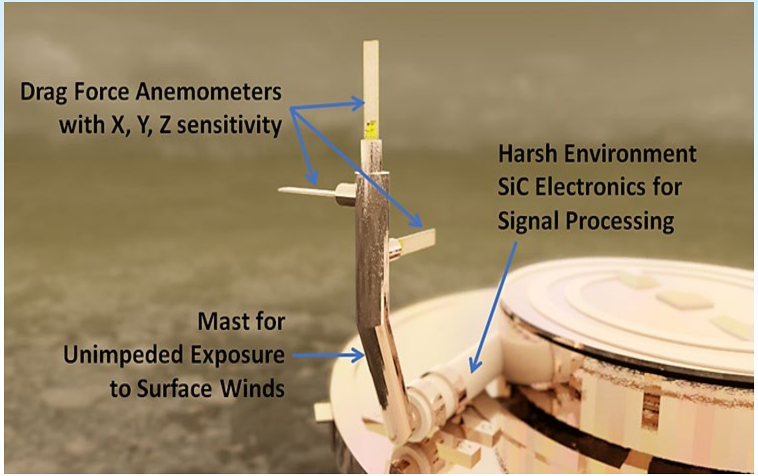
LLISSE Surface Wind Sensor

Background: ***Drag-force anemometer (cantilever) baseline approach with significant history of demonstrations in engine environments***

- Full-bridge strain gage approach allows flow measurements with minimal power consumption
- Force of wind bends cantilever; deformation measured using thin film strain gages
- Wind speed/direction determined using up to 3 perpendicular cantilevers along each axis

Current Status*: Wind sensor tested in wind tunnel and multiple times in GEER environment showing viability of approach*

- Core material compatibility demonstrated
- Wind sensor integrated with electronic amplification has shown ability to track gas flow in GEER-simulated Venus surface conditions



LLISSE Wind Sensor Approach

LLISSE Wind Sensor Assembly and Installation