A Brief Overview of High Temperature Technologies for Venus Surface Applications: Venus Sample Capture

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Outline

- Introduction
- Venus Technology Plan
- Venus Surface Platform Study
- Long Lived Platform Development
  - Electronics
  - Sensors
  - Communication
  - Power
- Actuation
- Summary and Future Prospects

Introduction

- 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
- This presentation will provide a sampling of high temperature development and technologies that may have an impact on future Venus exploration, esp. as relevant to Venus Sample Capture
  - What can be done now on the surface
  - What is in development
  - What are the future prospects

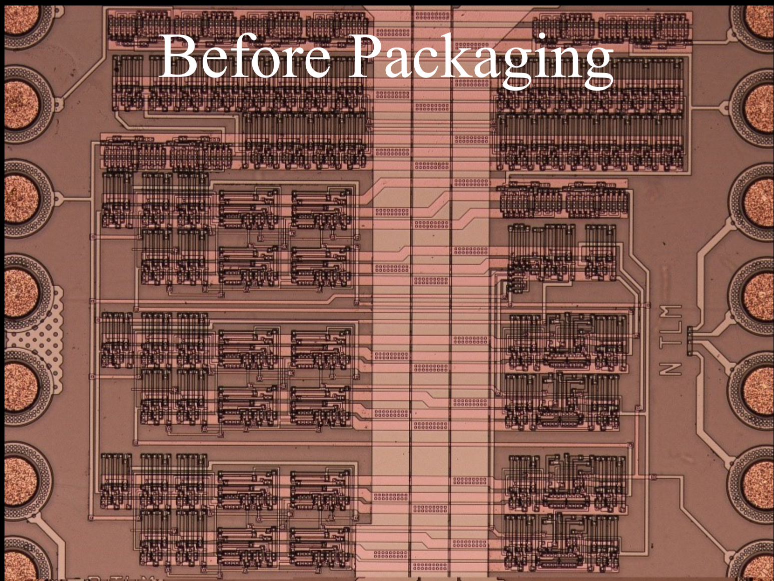
Technology Development Overview

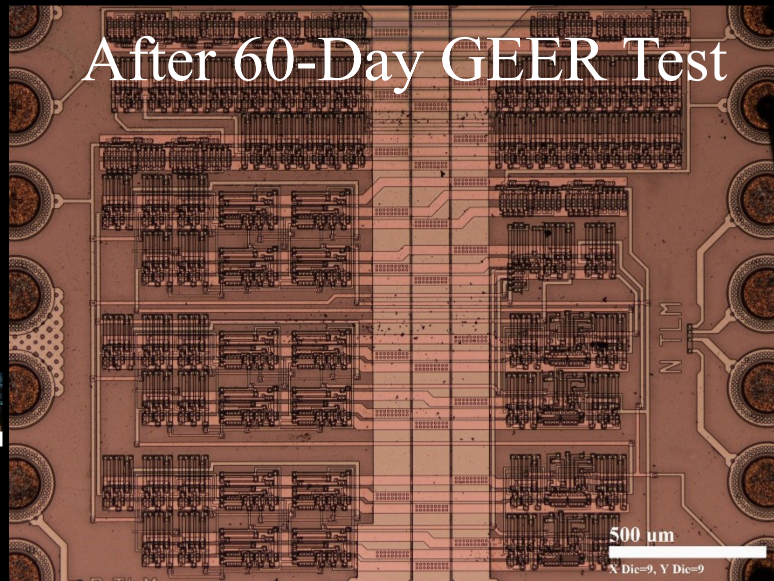
- Technologies relevant for Venus surface applications may often have their origin in other harsh environment applications e.g., aeronautics or industrial processing
- Material systems and engineering approaches standardly used for even harsh environment terrestrial applications may not be viable for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

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

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

VEXAG Venus Technology Plan
2019

VEXAG Technology Plan 2019
Generic Mission Descriptions

	Mission Mode	Generic Description
Near-Term	Orbiters- Fixed	Orbiters for investigations including surface, interior, atmospheric, and ionosphere
	Small Sat	A single small or cube sat conducting a focused science investigation
	Deep Probe	A probe characterizing the environment down to the surface
	Multiple Shallow Probes	Shallow probes or skimmers characterizing the upper-mid atmospheres
	Short Lived Large Lander	A short lived lander comprised of a conventional electronics instrument suite
	Aerial Platform Fixed	Aerial platforms with ability to operate in the atmosphere for sustained periods, but without flight control
Mid-Term	Advanced Orbiters	Highly complex orbiter systems with increasingly capable instrument array and limited ability to independently carry out and optimize investigations
	Multiple Deep Probes	Deep probes and sondes coordinated with aerial platform operations and each other
	Subsatellite/ Small Sat Platforms	Communication and observations systems able to provide a multiple scientific investigations as well as a communications and navigation infrastructure
	Aerial Platforms: Altitude Control Upper and Mid Cloud	Aerial platforms operating in mid and upper clouds with ability to control altitude
	Increased Duration Large Lander	A lander comprised of advanced thermal thermal protection extending life to 12 hours or more, and increasingly capable conventional electronics instrument suite
Far-term	Small Platform Lander-Long Duration	Small in situ platforms capable of operating at Venus ambient conditions to accomplish focused science investigations
	Advanced Orbiter /Smallsat Networks	An orbiter network composed of advanced orbiters and small sats providing coordinated science and mission communications support
	Aerial Platforms: Altitude Control All Cloud	Aerial platforms with ability to operate in the atmosphere for sustained periods throughout the various cloud altitudes
	Lander -Cooled Long Duration	A complex long-lived cooled landed systems with a suite of advanced earth-ambient temperature instruments
	Lander Network	A number of lander systems coordinated and linked in multiple scientific investigations, which are composed of a mixture of increasingly complex high temperature landers
	Mobile Surface	Mobile laboratory systems able to travel significant distances on the surface
	Sample Return Clouds	Sample recovery and return from the upper atmosphere
	Sample Return Surface	Sample recovery and return from the surface

VEXAG Technology Plan 2019

Near-Term 2018 to 2022 : We Can Do A Lot Now

		Near-Term Missions					
		Orbiters	Aerial Platform Sustained	Deep Probe	Multiple Shallow Probes	Multiple Shallow Sondes	Lander
System Technologies	Aerobraking						
	Entry ↑						
	Descent and Deployment						
	Landing						
	Aerial Platforms						
	Landers - Short Durations ↑						
Subsystem Technologies	Energy Storage- Batteries						
	Energy Generation - Solar						
	Thermal Control - Passive						
	High temperature mechanisms ↑						
	Medium temperature electronics ↑						
	Communications						
	Guidance, Navigation and Control ↑		MM				MM
	Remote Sensing - Surface						
Instrum ent	Remote Sensing -Atmosphere						
	Probe - Aerial Platform						
	In Situ Surface - Short Duration ↑						

Key

	Not applicable
	Very High. Ready for flight. Same as TRL 6
MM	Mix of Maturity. Some ready for flight but others at various maturity levels
↑	Notable advancements since the last Plan

VEXAG Technology Plan 2019
Evalutation Criteria

Key

	Not applicable	
(green)	Very High. Ready for flight in this timeframe. Same as TRL 6	Established for flight.
(light green)	Moderate to High. Limited development and testing still needed	Defined transitioned to flight.
(yellow)	Moderate- Active on-going R&D effort needed for readiness in this given timeframe.	Presently understood technical pathway to achieve capability by this timeframe.
(orange)	Moderate to Low: Significant R&D effort needed for readiness in this timeframe	A viable foundation exists, but more than one technical pathway in consideration to achieve capability by this timeframe.
(red)	Low. Major R&D effort needed with notable technical challenges.	It not clear how to achieve the targeted capability and basic research activities in multiple fields may be needed to achieve this capability by this timeframe.
⬆	Notable advancements since the last	

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

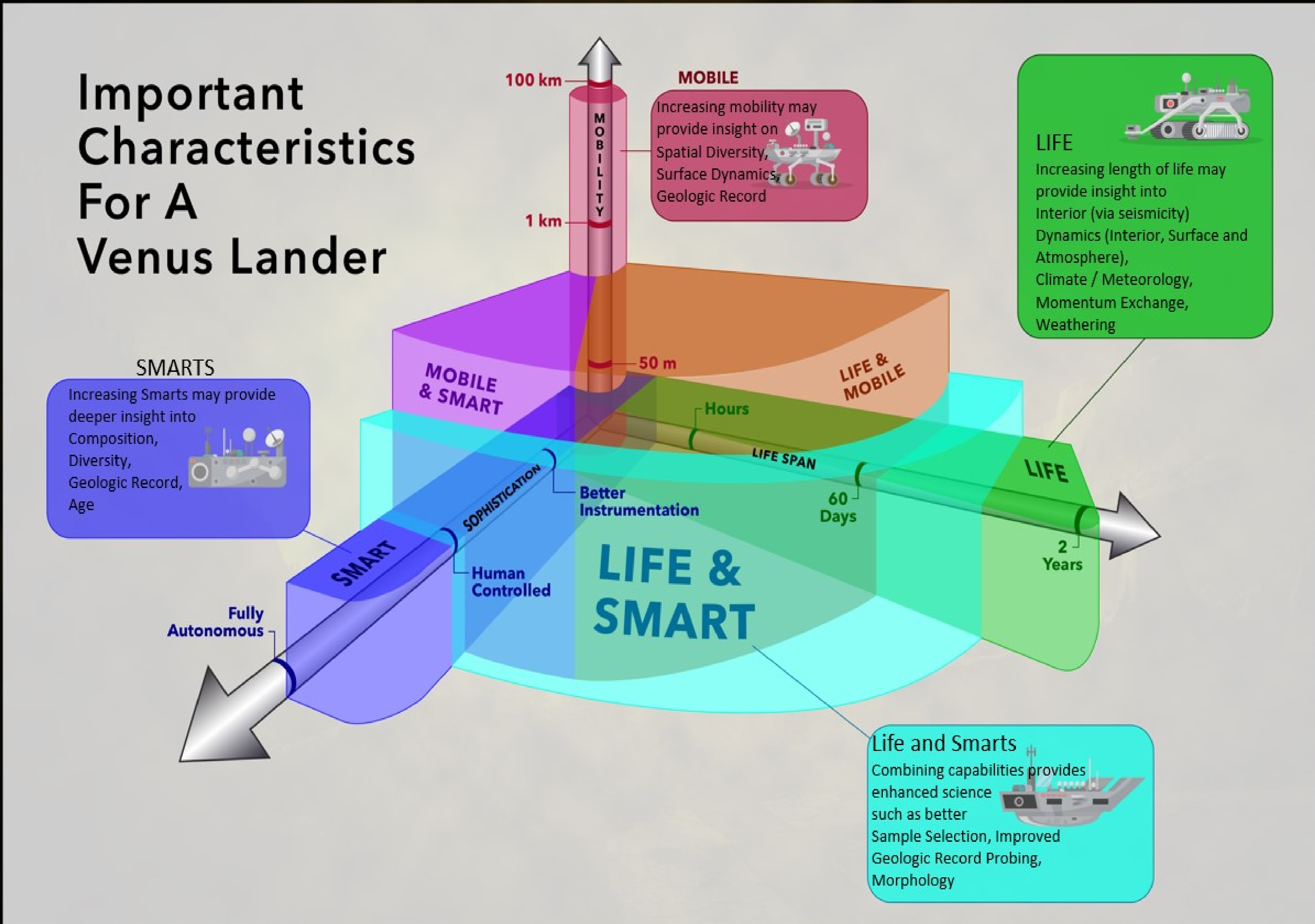
	Mission Mode	Mid-Term Missions: Advanced Orbiters	Subsatellite/ Small Sat Platforms	Multiple Deep Probes and Sondes	Increased Duration Large Lander	Small Platform Lander-Long	Aerial Platforms Altitude. Control Upper and Mid Cloud
System Technologies	Aerocapture						
	Entry ↑						
	Descent and Deployment ↑						
	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						

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

	Mission Mode	Far-Term Missions						
		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							

Venus Surface Platform Study
On-Going
Leads: T. Kremic and M. Amato

Venus Surface Platform Study
Lander Characteristics



Venus Surface Platform Study
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

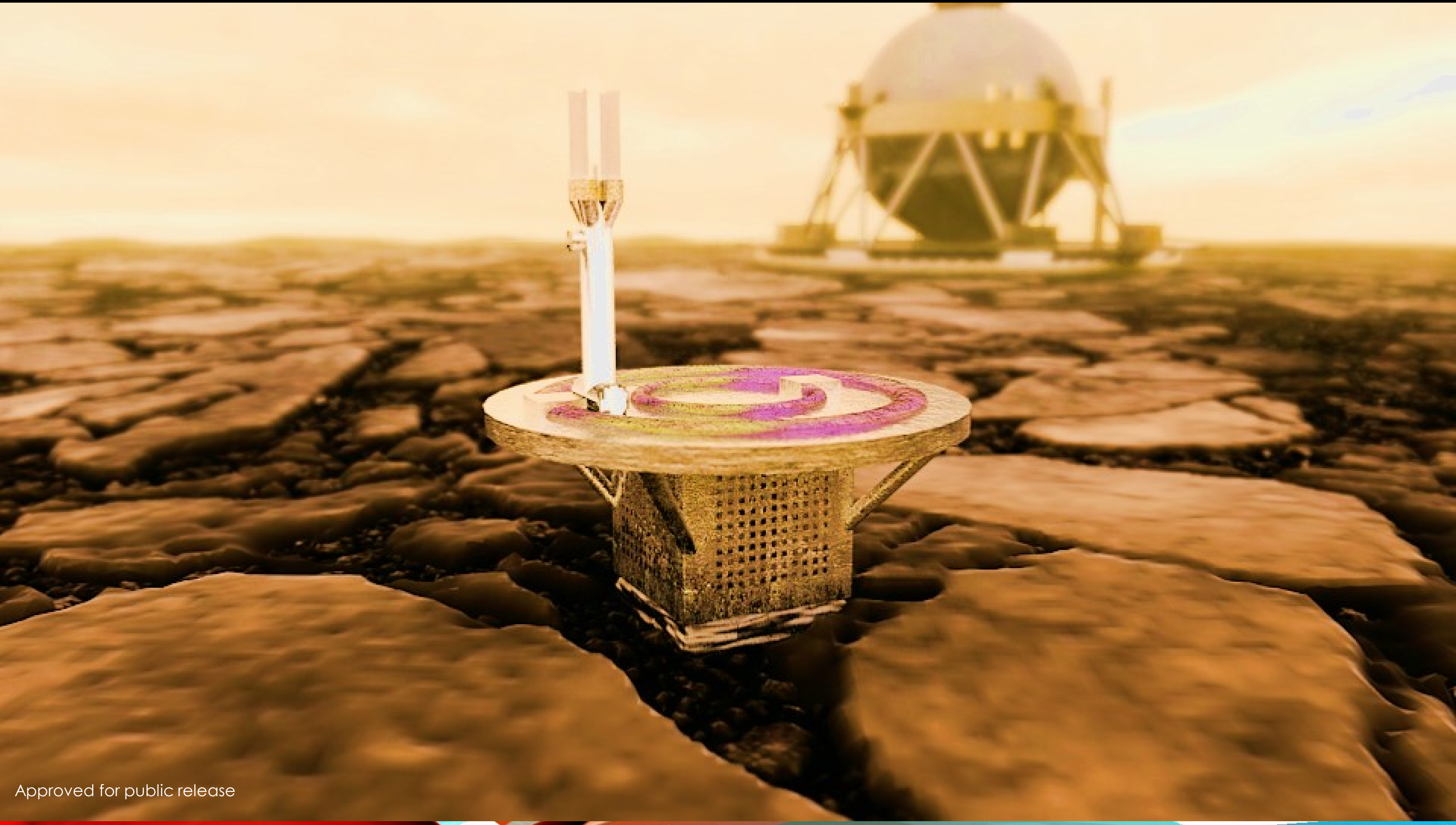
	Capability		
Technology	Time	Smarts	Mobility
Power (L – low, 10's of watts or less)	H	H	
Power (H - high, 100's of watts)			H
Cooling (Needs Power H)	S	H	
High Temp Electronics / Memory	H	H	H
Mechanisms (Drills, Wheels, ...)	S	S	H
Autonomous Ops, Nav	S	H	H
SOA Instruments	H	H	H

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.

Long Lived Surface Platforms Development
LLISSE, SAEVe, HOTTech, etc.

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

PI TIBOR KREMIC, NASA GLENN



Approved for public release

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

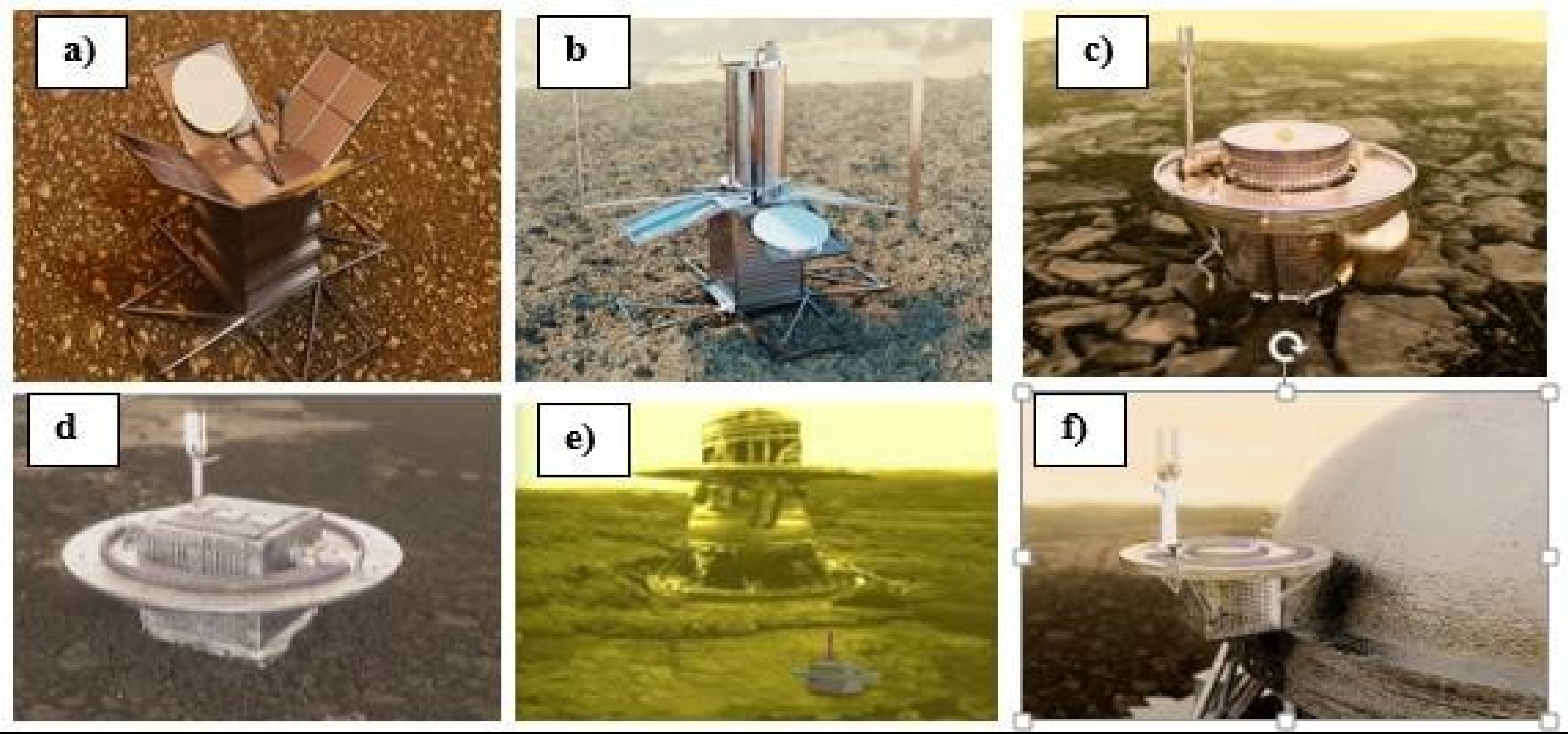
- LLISSE is a small and "independent" probe for Venus surface applications
- LLISSE acquires and transmits simple but important science
- Three key elements leveraged
  - Recent developments in high temperature electronics
  - Focused, low data volume measurements
  - Novel operations scheme

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

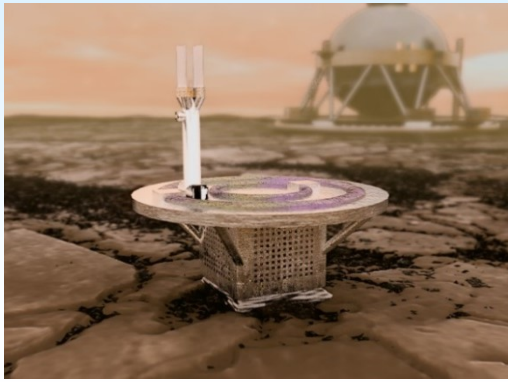
An Approach to achieve a class of long-lived landers for Venus



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 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.
    - ➢ Sensor systems for acquiring temporal meteorological and key atmospheric species data, momentum exchange between surface and atmosphere, and the rate of solar energy deposition.
    - ➢ Communications for data transfer from the Venus surface to an orbiter including circuit and antenna design. Determination of lander orientation.



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

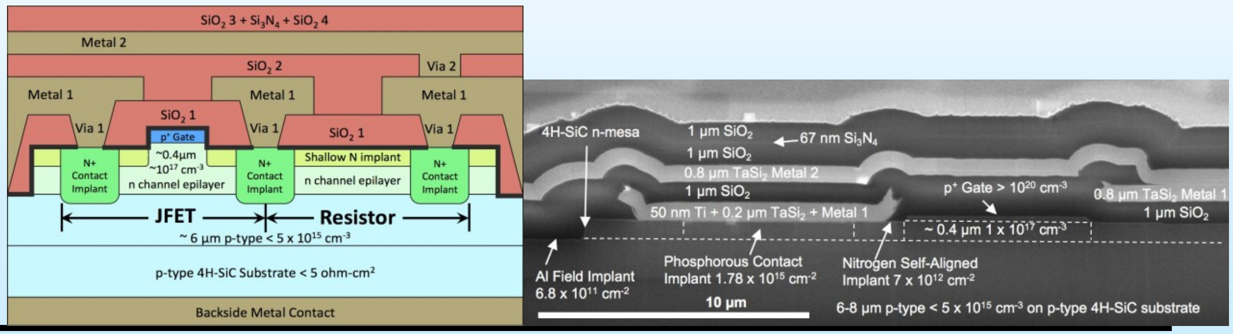
Electronics

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



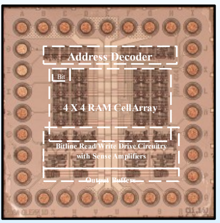
NASA GRC Electronics Development

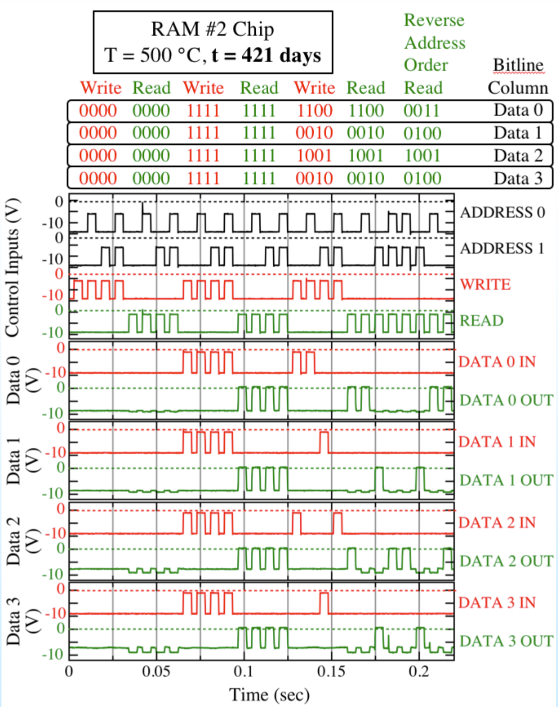
2017 NASA Glenn SiC JFET IC "Version 10"
1+ year of operation in Earth air oven at 500 ° C Achieved

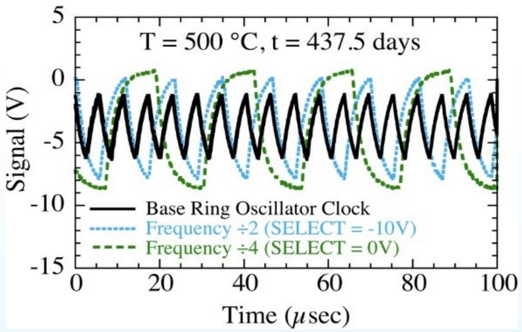
Version 10 ICs continue to **set high temperature durability world records in T ≥ 500 °C Earth-atmosphere oven testing.**

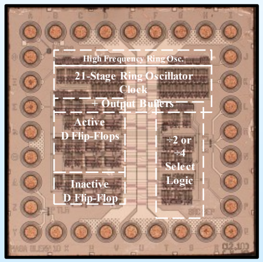
Complex ICs Operating more that 1 Year at 500 °C[1]

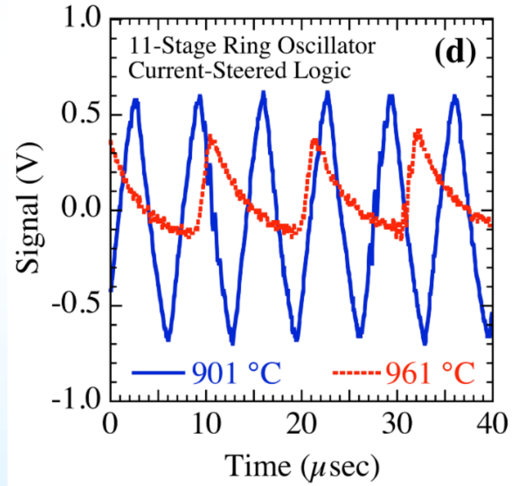
ICs Operating at World Record 961 °C[2]











[1] 2018 Int. Conf. High Temperature Electronics p. 71

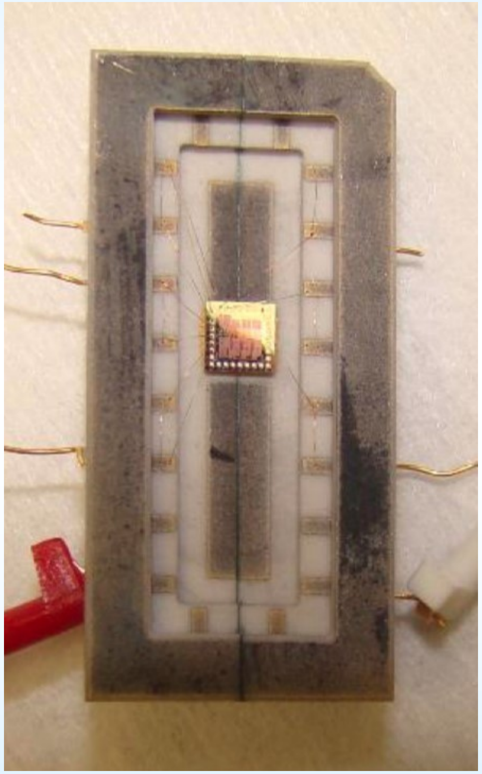
[2] IEEE Electron Device Letters vo. 38 p. 1082 (2017).

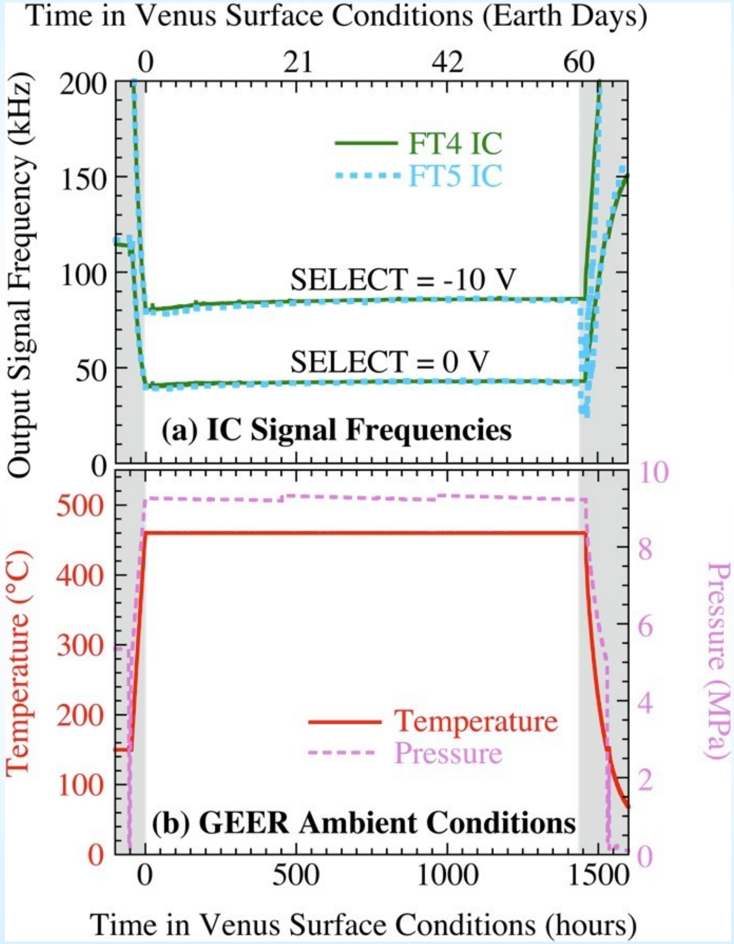
60-Day Venus Environment IC Test (in GEER)[1,2]

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





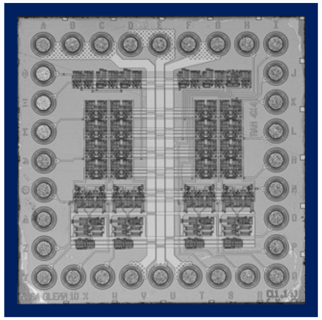
[1]Neudeck et al., IEEE J. Electron Devices Soc., vol. 1, p. 100 (2018).

[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.

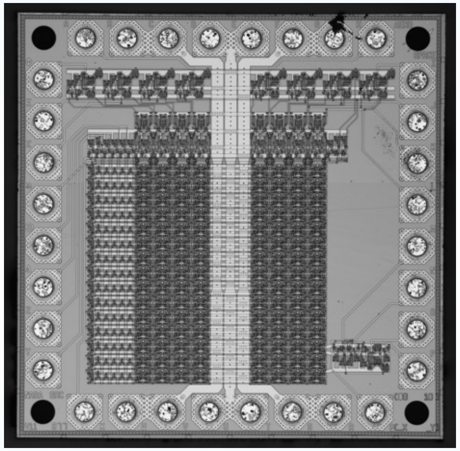
"IC Gen. 10" (2017)
(16-bit RAM, 195 SiC JFETs)
2 prototype 75 mm diameter SiC epi-wafers
6 μm gate length, 6 μm resistor width
3 mm x 3 mm, 32 I/O Bond Pads



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)

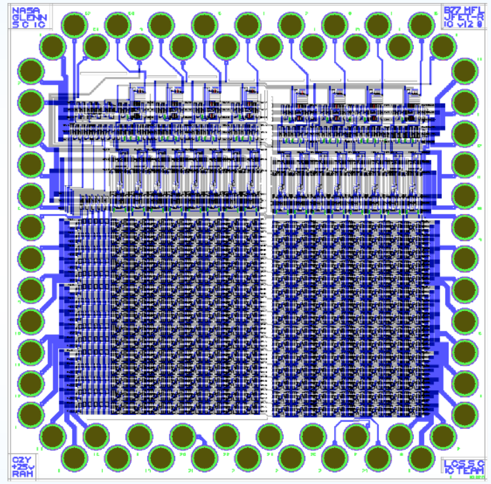
"IC Gen. 11" (2018)
(120-bit RAM, ~ 1000 SiC JFETs)
4 prototype 75 mm diameter SiC epi-wafers
6 μm gate length, 3 μm resistor width
4.65 mm x 4.65 mm, 32 I/O Bond Pads



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

"IC Gen. 12" (2021)
(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



Wafer fabrication in progress, but completion delayed by COVID-19 on-site work restrictions until at least late 2021.

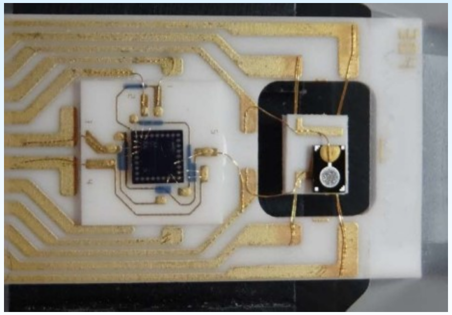
*Published results, see https://www1.grc.nasa.gov/research-and-engineering/silicon-carbide-electronics-and-sensors/technical-publications/

Example Sensors/Instruments

LLISSE Sensors Summary

Broad Array Of Sensor Technology For Venus Applications Leveraged From Aeronautics Development

- Long History Of Active Development of Harsh Environment Smart Sensors Systems For Engine Test Stand, Health Management, and Intelligent Engines
- Multiple Demonstrations/Applications e.g., Including On-wing Engine Testing



Courtesy of D. Makel, Makel Engineering, Inc.

SiC Electronics Combined With Chemical Sensor for GEER Testing

Development Approach

- Miniaturized Sensor Systems Produced By Microfabrication Techniques and High Temperature Compatible Materials
- Parallel Development Of Multiple Sensor Types
  - Multiple Chemical Species
  - Temperature
  - Wind (3 Directions)
  - Pressure
  - Radiance
- Each Sensor Has Targeted Specifications and Associated Electronics Requirements

High Temperature Pressure Sensor

Status

- Several Sensors Have Reached High Levels of Maturity For This Application
- Integration of Multiple Sensor Types with SiC Electronics Demonstrated

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

Status: ***Development of Chemical Sensors*** *(including GRC sensors)* ***Integrated with NASA GRC SiC Electronics On-Going in HOTTech project***

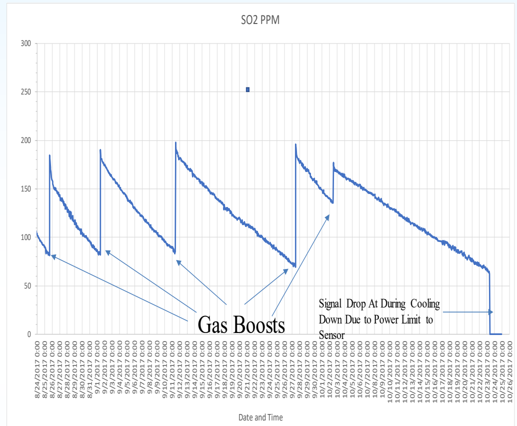
Four Chemical Microsensors (SO_2, CO, OCS, HF) Tested for 60 days in Venus Simulated Conditions in GEER

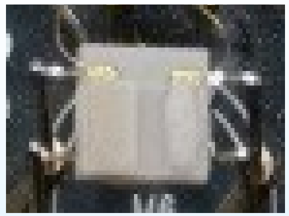
- All 4 Sensors Operated Nominally During 60 Day Test
- First Demonstration of In-Situ SO_2 Tracking in GEER for Extended Periods

- HF Sensor Integrated With Signal Transduction/Amplification SiC Electronics Monitored HF Boosts in GEER 10 Day Test

TRL Summary: Four chemical sensors successfully tested in Venus conditions for 60 days with SO2 sensor tracking concentration changes and consistent with gas chromatograph readings. HF sensor with SiC electronics responded to concentration changes in 12 day testing.

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





SO_2 MicroSensor

Venus In Situ Surface Imager (VISSI)

PI: Jeffrey Balcerski, Ohio Aerospace Institute

Target Application: Venus surface – long duration

Science:
- Obtain high resolution digital images of the surface of Venus at multiple scales
- Resolve geologic features near landing site at a resolution of 1 mm/px at 1 m
- Observe transient phenomena (i.e. active sediment transport) over the period of days to weeks
- Resolve basic rock and mineral types via optical filters

Objectives:
- Develop imaging array of high-temperature photodiodes sensitive to visible spectrum
- Develop high-temperature electronics to produce transmit-ready digital image data
- Identify and integrate appropriate optical lenses and filters
- Test and demonstrate the operation of all components at Venus surface conditions for extended time (days to weeks)

CoIs: Gary Hunter, Geoffrey Landis, Phillip Abel – NASA Glenn Research Center; Martha Gilmore – Wesleyan University

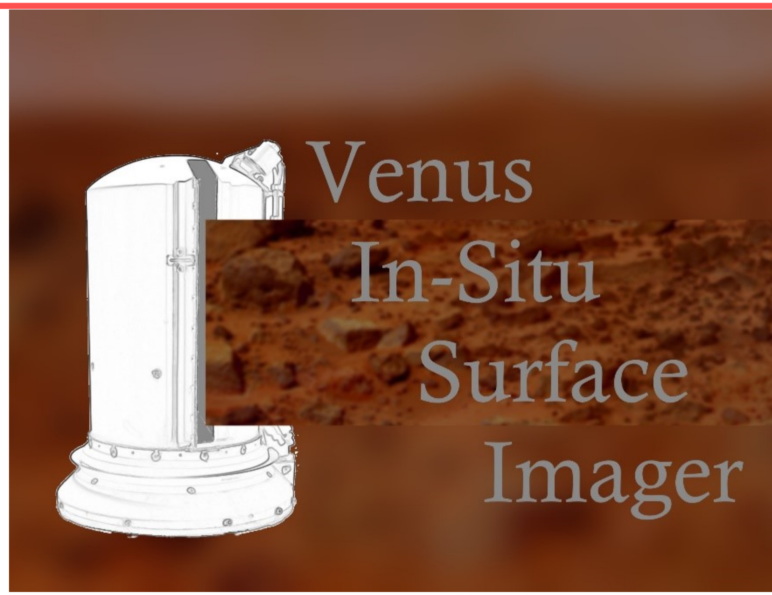


Figure Caption: A new generation imager for the surface of Venus.

Planned Key Milestones (Tentative Based on Facility Availability/Pre COVID):
- 4Q FY19: Performance requirements for VISSI
- 3Q FY20: Demonstrate Photodiode and Amplification at 500ºC
- 3QFY20: Demonstrate Photodiode for 60 days at 500ºC
- 2Q FY21: First generation VISSI electronics evaluated at 500ºC
- 4Q FY21: Integrated photodiode array and electronics providing image at 500ºC
- 3QFY22: Image produced at 500ºC
- 4Q FY22: VISSI proof-of-concept demonstration in Venus simulated conditions

TRL 3 to 4

Communications

LLISSE Communications Summary

History of Cutting Edge Development in High Temperature Wireless Communications

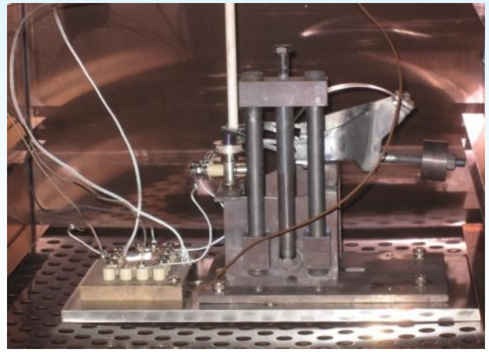
- Wireless Signal Spectra For High Temperature Seismometer Sensor Displacements Demonstrated (2012)
- Demonstrated Wireless Pressure Sensor At 475ºC Including Pressure Sensor, SiC Circuitry, and Wireless Circuit (2013)

Development Approach

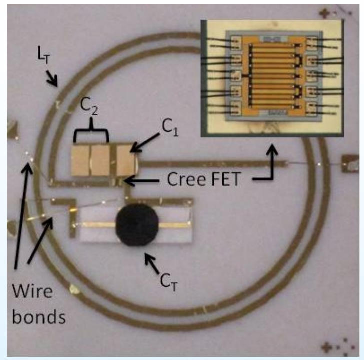
- Activities Include Venus Relevant Development Of Antennas, Transmitters, and Other Components
- Increasing Capabilities and Complexity of High Temperature Electronics Circuits Increases Communication System Capabilities
- Targeted Operation of Communication System from 100 to 150 MHz.

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

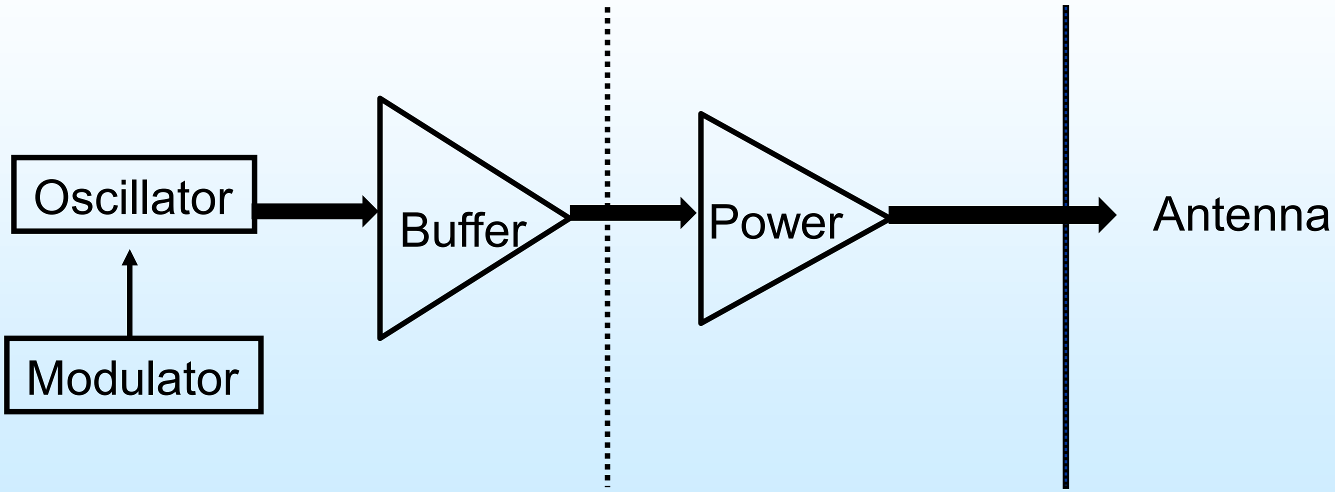


Wireless Pressure Sensing Circuit

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



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^{0}C
Environment: Venus Surface @ 90 Bar

Configuration

Volume: 1.07 liters
Weight: 2.83 kg
2.39 Ampere-Hours
95.6 Watt-Hours @ 40 V
89 Watt-Hour/liter

1/6 Scale Battery

Test Hardware S/N 002-005 cells;
S/N 006 & 007 Batteries

HOTTech Project Technology Areas

	Technology Area	HOTTech Tasks	PI	Organization
1	Packaging	500°C Capable, Weather-Resistant Electronics Packaging for Extreme Environment Exploration	Simon Ang	University of Arkansas
2	Clocks & Oscillators	Passively Compensated Low-Power Chip-Scale Clocks for Wireless Communication in Harsh Environments	Debbie Senesky	Stanford University
3	GaN Electronics	High Temperature GaN Microprocessor for Space Applications	Yuji Zhao	Arizona State University
4	Computer Memory	High Temperature Memory Electronics for Long-Lived Venus Missions	Phil Neudeck	NASA GRC
5	Diamond Electronics	High Temperature Diamond Electronics for Actuators and Sensors	Bob Nemanich	Arizona State University
6	Vacuum Electronics	Field Emission Vacuum Electronic Devices for Operation above 500 degrees Celsius	Leora Peltz	Boeing Corp.
7	ASICs & Sensors	SiC Electronics To Enable Long-Lived Chemical Sensor Measurements at the Venus Surface	Darby Makel	Makel Engineering, Inc
8	Primary Batteries	High Temperature-resilient And Long-Life (HiTALL) Primary Batteries for Venus and Mercury Surface Missions	Ratnakumar Bugga	NASA JPL
9	Rechargeable Batteries	High Energy, Long Cycle Life, and Extreme Temperature Lithium-Sulfur Battery for Venus Missions	Jitendra Kumar	University of Dayton
10	Solar Power	Low Intensity High Temperature (LIHT) Solar Cells for Venus Exploration Mission	Jonathan Grandidier	NASA JPL
11	Power Generation	Hot Operating Temperature Lithium combustion IN situ Energy and Power System (HOTLINE Power System)	Michael Paul	JHU/APL
12	Electric Motors	Development of a TRL6 Electric Motor and Position Sensor for Venus	Kris Zacny	Honeybee Robotics, Inc.

High Temperature Batteries for Venus Surface Missions

R. V. Bugga, D. Glass, J. P. Jones, A. Shevade (JPL), E. Raub and D. Bhakta (EaglePicher Technologies)

Goal and Objective

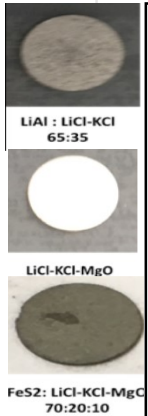
- Develop an enabling battery for Venus surface missions, (30 d at 475°C (and 92 bar).
- LISSE (NASA GRC Lander) goal: 60 days

Previous Venus surface missions lasted <2 h.

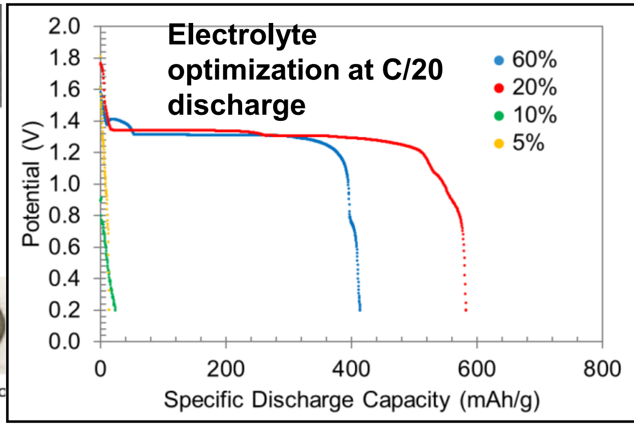
Battery Chemistry

- Anode (Li alloys, e.g., Li-Al, Li-Si)
- Cathodes
  - Metal Sulfides: FeS, FeS_2, CoS_2, NiS_2, TiS_2
  - Metal Phosphorous Trisulfides: $FePS_3$, $NiPS_3$
- Molten salt electrolyte (mixed alkali metal halides)
  - LiCl-KCl (44 wt% LiCl and 56 wt% KCl) (m.p.359°C)
- Separators (MgO, Al_2O_3, Li_2O)

Components



Li(Al)-FeS Laboratory cells @ 475°C

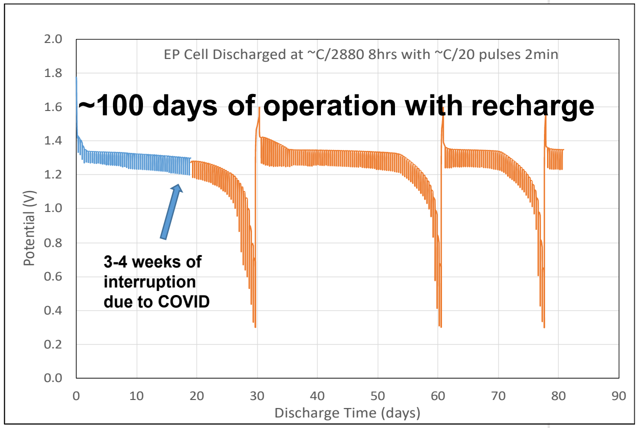


- Poor cathode utilization at low discharge rates due to cathode dissolution in electrolyte.
- Electrolyte formulation developed to extend cell lifetime; Demonstrated >20 days of operation in laboratory cells at 475°C
- Low electrolyte and high binder content reduce self discharge.

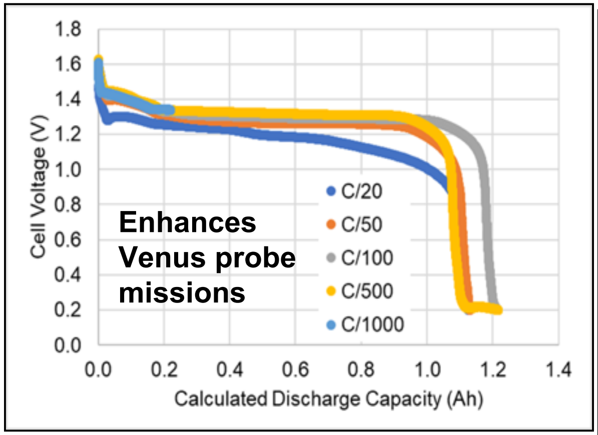
Prototype Cells

- Cells fabricated with JPL recipe and materials
- Leverage EaglePicher's expertise in thermal batteries

Prototype Cells



Prototype Cells



Path Towards Infusion

- Improve chemistry (for 60 day operation).
  - 50% improvement with cathode coating
  - New electrolytes and cathode materials
- High pressure design
- Bipolar cell stack
- GEER Testing of cells and batteries
- Battery qualification in Venus environments.

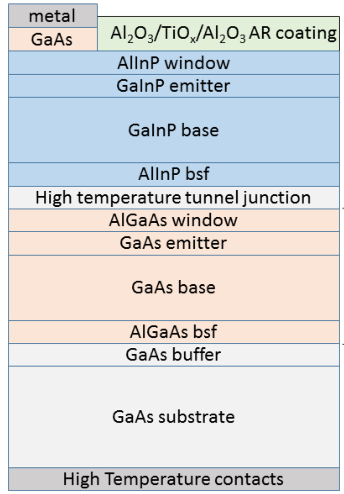
D. Glass, J. P. Jones, A. Shevade, D. Bhakta, E. Raub, R. Sim and R. V. Bugga, J. Power Sources, 449 (2020) 227492;

Low Intensity High Temperature (LIHT) Solar Cells for Venus Exploration Missions

Objective: Fabricate a solar cell that can operate at 300C and 21 km altitude and survive at the surface of Venus.

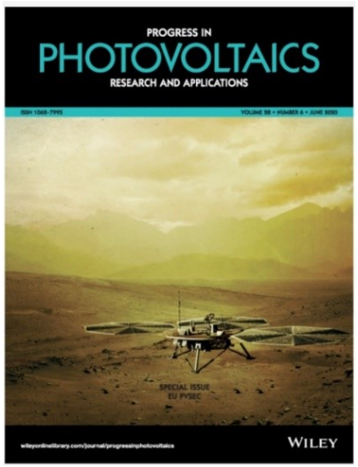
Highlights:

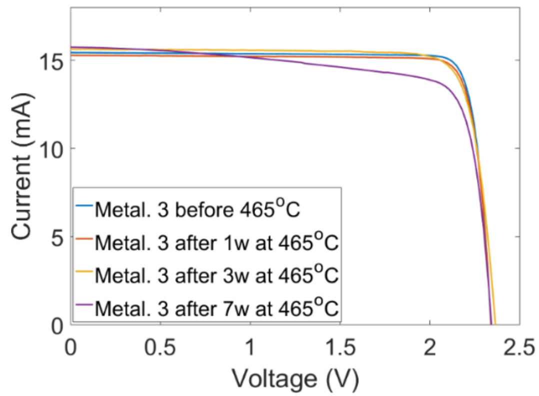
(1) Fabrication of LIHT solar cells.
(2) Device modeling of LIHT solar cells at various altitudes of the Venus atmosphere.
(3) Demonstration of LIHT solar cells with 16% efficiency at 300C under a simulated 21 km altitude Venus solar spectrum.



Simplified cross-section schematic of a GaInP/GaAs 2J solar cell designed for high temperature operation.

(4) Survive at 465C Venus surface temperature for more than 1 month.
(5) Photovoltaics operation at the surface of Venus.





-V response (AM0 spectrum) rom a Gen 2 GaInP/GaAs 2J solar cell with high temperature grid metal before and after heating at 465°C for up to 7 week.

Publications:

J. Grandidier, A. P. Kirk, M. L. Osowski, P. K. Gogna, S. Fan, M. L. Lee, et al., "Low-Intensity High-Temperature (LIHT) Solar Cells for Venus Atmosphere," *IEEE Journal of Photovoltaics*, vol. **8**, pp. 1621-1626, 2018.

J. Grandidier, A. P. Kirk, P. Jahelka, et al., "Photovoltaic Operation in the Lower Atmosphere and at the Surface of Venus," *Wiley Progress in Photovoltaics*, vol. 28, pp. 545-553 (2019).

The HOTLINE Power System

Hot Operating Temperature Lithium combustion for IN situ Energy and Power

PI: Michael Paul, Johns Hopkins Applied Physics Lab
Co-PI: Dr. Alex Rattner, Penn State University

Target: Venus

Science: Long duration surface geology and atmospheric measurements

Objectives:

- Demonstrate Rankine power system designed for Venus surface operating conditions.
- Characterize power levels, efficiencies

Key Milestones

Year 1

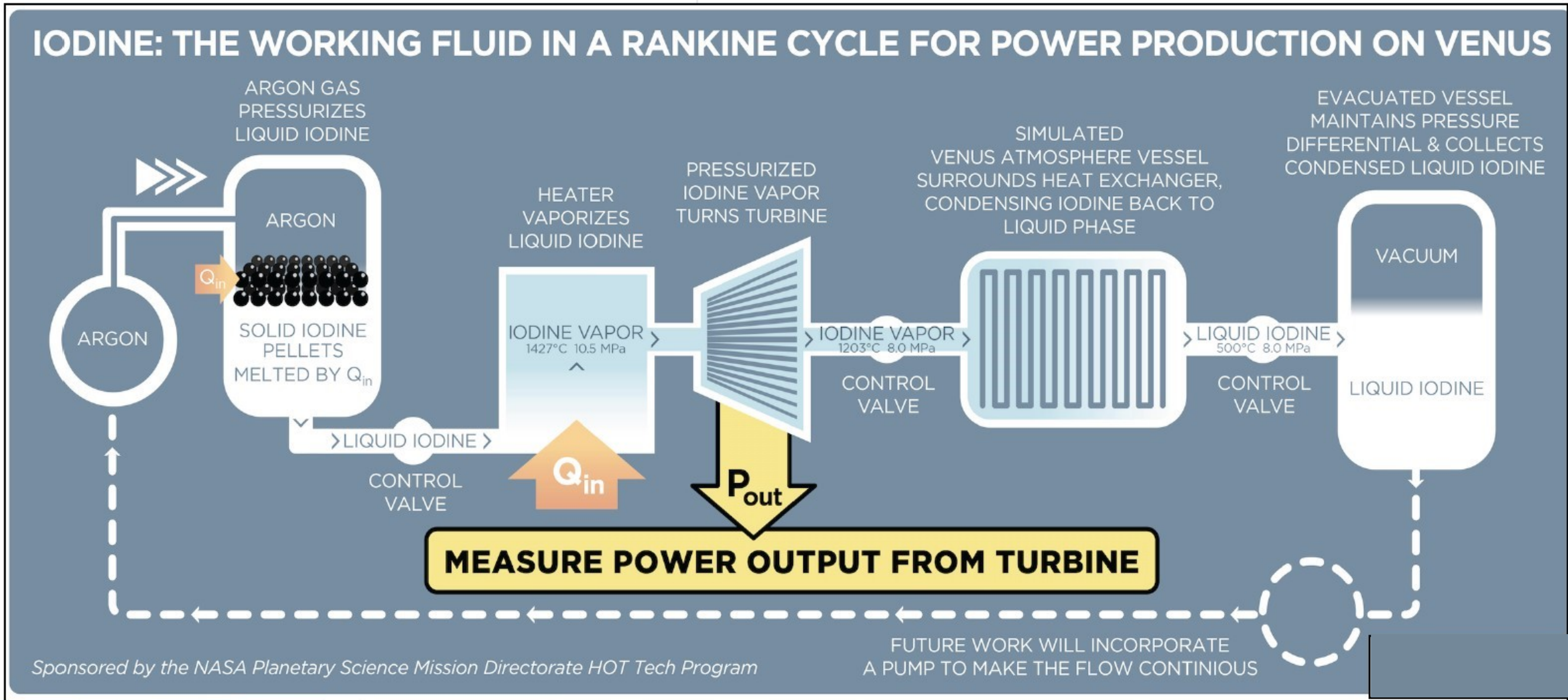
- Flight power system high level definition
- Test system (below) detailed design

Year 2

- Test system fabrication
- Test system checkout

Year 3

- High temperature power tests



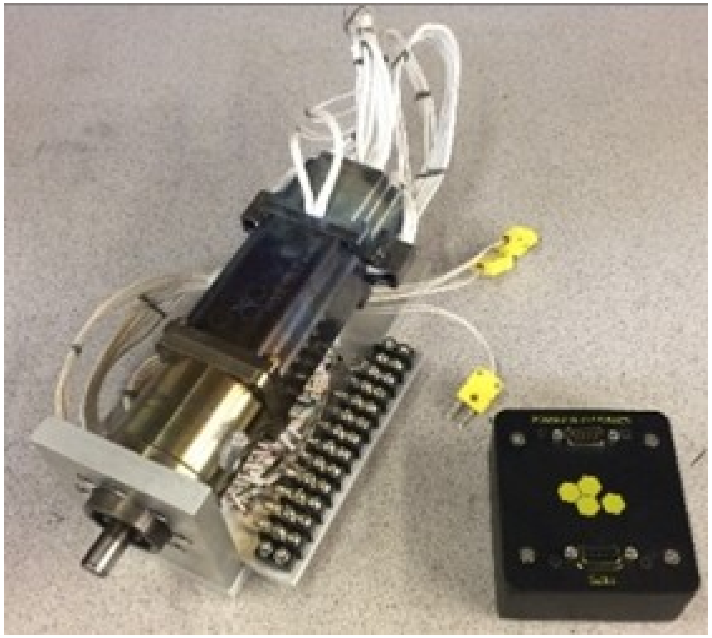
Actuation

High Temperature Venus Motor

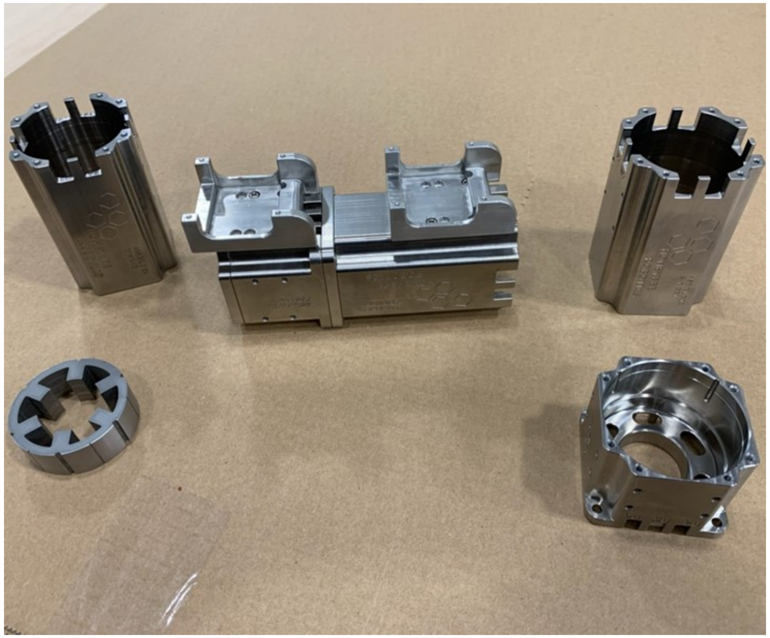
HONEYBEE ROBOTICS
Exploration Technology

- High temperature motor, gearbox and Pulsed Injection Position Sensor (~Resolver)
- Under development via SBIR and HOTTech since ~2007
- Power: ~ 100 Watt (scalable)
- Can be used as generator

Actuator: Planetary gearbox, BLDC Motor, PIPS sensor



Housing, magnets etc.



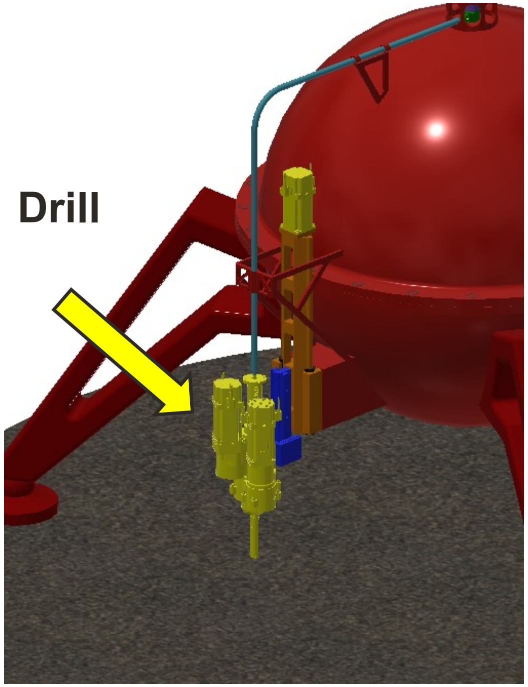
Coils

Courtesy: K. Zacny

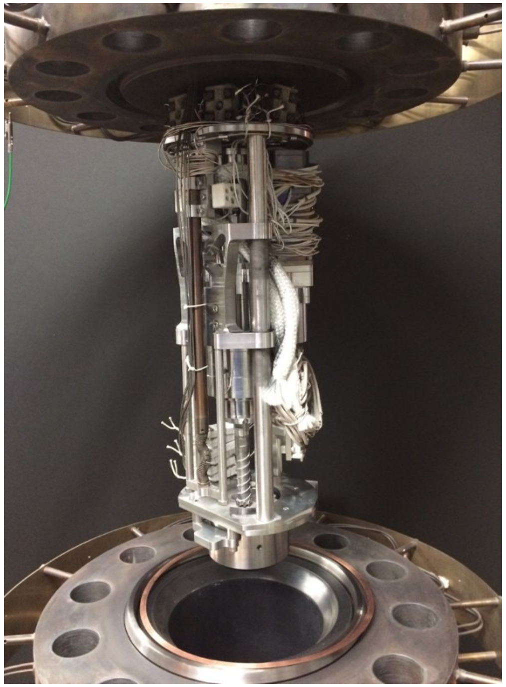
High Temperature Hammer Drill

HONEYBEE ROBOTICS
Exploration Technology

- Developed for NF Venus In-Situ Explorer mission, called VISAGE (lead JPL)
- Several tests at Venus conditions at JPL (P, T, CO_2)
  - 4 mm/min in 120 MPa basalt
- Coupled to JPL sample transport system
- Materials characterization for long duration missions at GEER

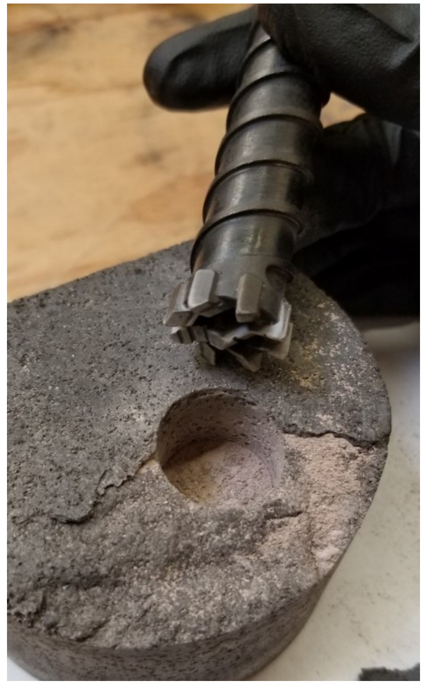


Rotary-Percussive Drill



JPL Venus chamber tests

Drilling in basalt



Courtesy: K. Zacny

Rover Studies for Venus

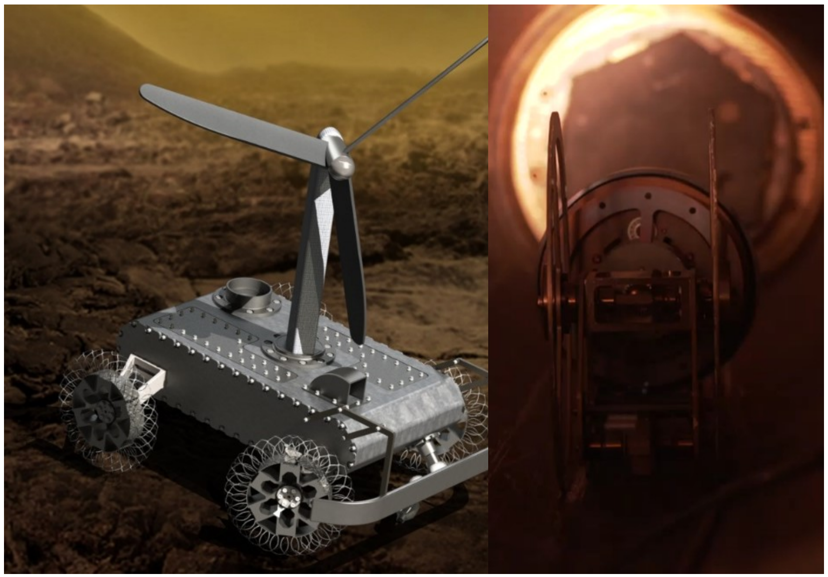
Courtesy J. Sauder, NASA JPL

Hybrid Automaton Rover – Venus (HAR-V) by Jonathan Sauder, NASA JPL

A wind powered, clockwork mechanism rover.

Basic Concept: Make the rover as simple and robust as possible.

Demonstrated key design elements at Venus Temperatures

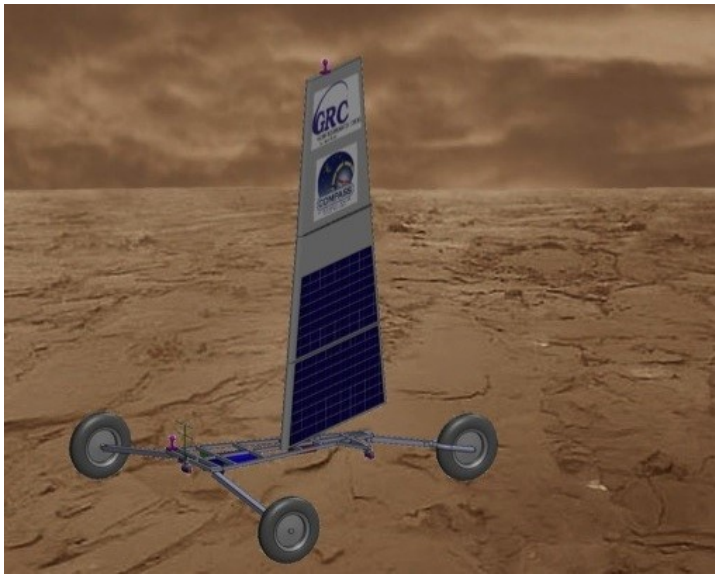


Zephyr – Land Sailing Rover by Geoff Landis, NASA Glenn

A wind driven rover on Venus.

Use solar for power during the Venus day.

Lightweight, with simple high temperature electronics.



Themes from Venus Rover Studies

Courtesy J. Sauder, NASA JPL

If you want a rover before the 2040's (and possibly much later)

- **Power: Mobility requires a lot of energy, which is hard to get on the surface of Venus.**
  - Converting through generators and motors would result in 90%+ energy loss.
  - Instead, use wind power to directly move the rover.
  - Slow speed, high force wind input provides slow speed, high torque output for mobility.
- **Autonomy: High temperature electronics can do simple operations.**
  - A Venus rover has to operate very differently than a Mars rover, with minimal onboard computing.
  - Consider how you can make the design robust, and operate in an "observe and report" mode for most operations.
  - This means completing rethinking the rover.
  - Use larger wheels than current rovers, to drive over average rocks.
- **Navigation (from HAR-V only): Need to detect obstacles, with a very limited sensor suite and during a 60 earth-day night.**
  - Can't use the traditional terrain relative navigation with image recognition software
  - Need to look at short range obstacle avoidance and detection.
  - Global navigation (avoid large circles) also presents a challenge.

SUMMARY AND FUTURE PROPECTS

- **Venus Surface Exploration Has Unique Technical Challenges Due To The Extreme Environment**
- **Venus Technology Plan: Future Venus Sample Return is Considered Very Challenging**
- **The Combination of Smarts, Mobility, and Extended Life is Enabling for Surface Lander Platforms**
  - **Impact On Both Science Delivered and Mission Capabilities**
- **A Range Of Harsh Environment Technologies Are In Development To Enable Long Life Surface Missions in e.g., LLISSE and HOTTech**
  - **Electronics, Packaging, Communications, Power, Actuation**
  - **LLISSE Is Moving Towards An Engineering Model By 2025**
  - **HOTTech I Awarded 12 Awards: Many Have Shown Progress To Demonstrate Functional Operation At Realistic Environmental Conditions.**
- **Recent Advances Have Been Significant And The Prospect Of Long-lived Missions On The Venus Surface Is Becoming Increasingly Viable**
- **Major Challenges Exist For Transitioning These Technologies Into Viable Surface Based Venus Sample Return**
- **Mission Designs Based the Evolving State of What Can Be Done on the Surface May Enable a Form of Venus Sample Return, but Perhaps Not Like Mars**

Backup

Venus Technolgy Plan Team Members

Gary Hunter, NASA Glenn (Chair)

Jeffery Balcerski, Ohio Aerospace Institute/NASA Glenn

Samuel Clegg, Los Alamos National Laboratory

James Cutts, NASA JPL

Candace Gray, New Mexico State University

Noam Izenberg, Applied Physics Lab

Natasha Johnson, NASA Goddard

Tibor Kremic, NASA Glenn

Larry Matthies, NASA JPL

Joseph O'Rourke, Arizona State University

Ethiraj Venkatapathy, NASA Ames

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.

HOTTech Project Technology Areas

How Technology Areas Map to Spacecraft Systems