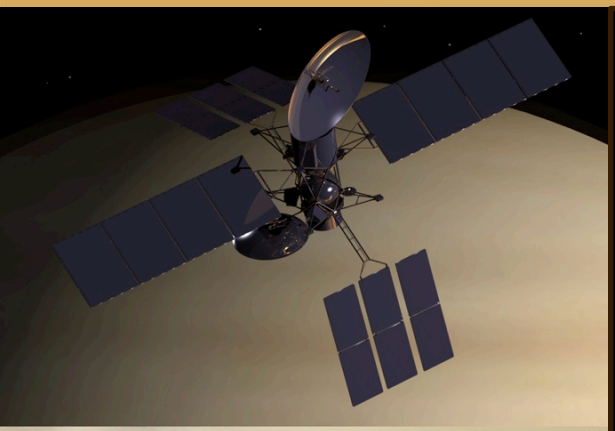
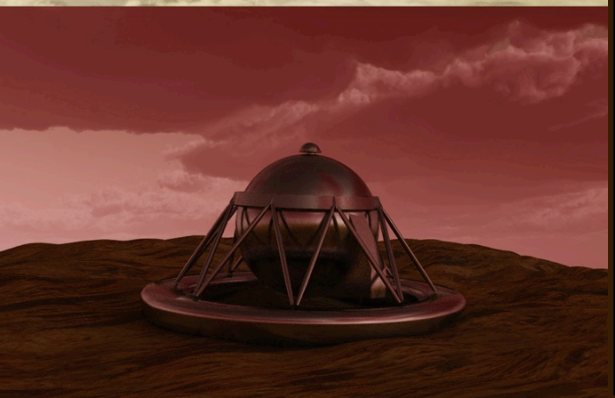




Subsystem Technologies for Venus Environments

James Cutts, JPL

International Planetary Probe Workshop 2016

June 11-12, 2016

Topics

- Overview
- System vs Subsystem Technologies
- Venus Environments
- What makes high temperatures so challenging?
- Key Subsystem Technologies for Venus Environments
  - Power
  - Navigation Guidance and Control
  - Electronics
  - Mechanisms
- Bibliography

Overview

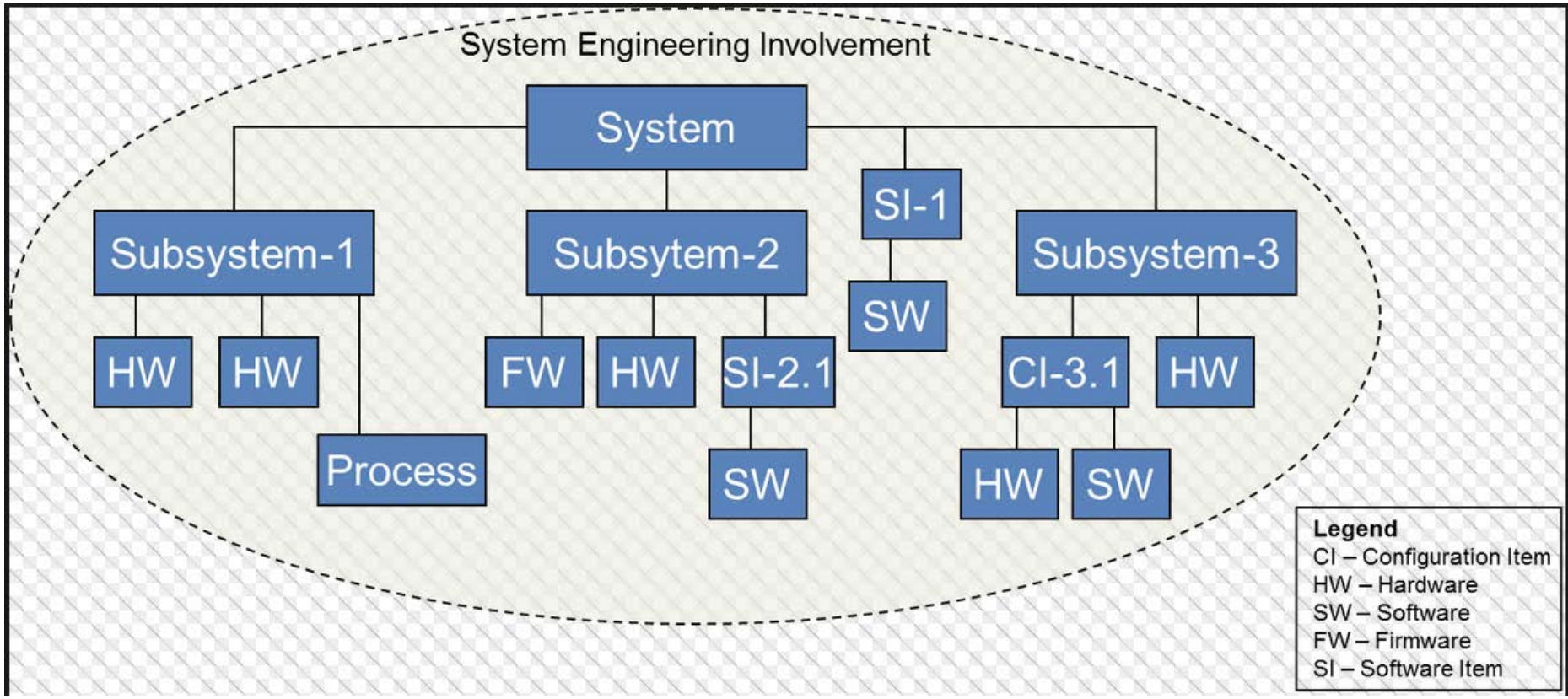
- In situ exploration of Venus faces formidable obstacles primarily because of the severe environments that are experiences

- This presentation focused primarily on technologies for surviving and operating in the severe environment of Venus and the developmental status of those technologies.

- The focus is on subsystems technologies that enable the systems capabilities for entry, descent, landing, flight and extended operations discussed in prior presentations

- It is also relevant to the scientific instrument techniques for landers, probes and aerial systems that will follow.

Systems vs Subsystems Technologies (1 of 2)



Key Subsystem Technologies for Venus

Spacecraft Systems

- Entry at Venus
- Descent to the Venus surface
- Landing and operating on the Venus surface
- Flight on Venus: Balloons and Aircraft

Subsystem Technologies

- Electronics
- Materials
- Communications
- Power
- Thermal Control
- Mechanical Systems
- Guidance Navigation and Control

Instrument Systems

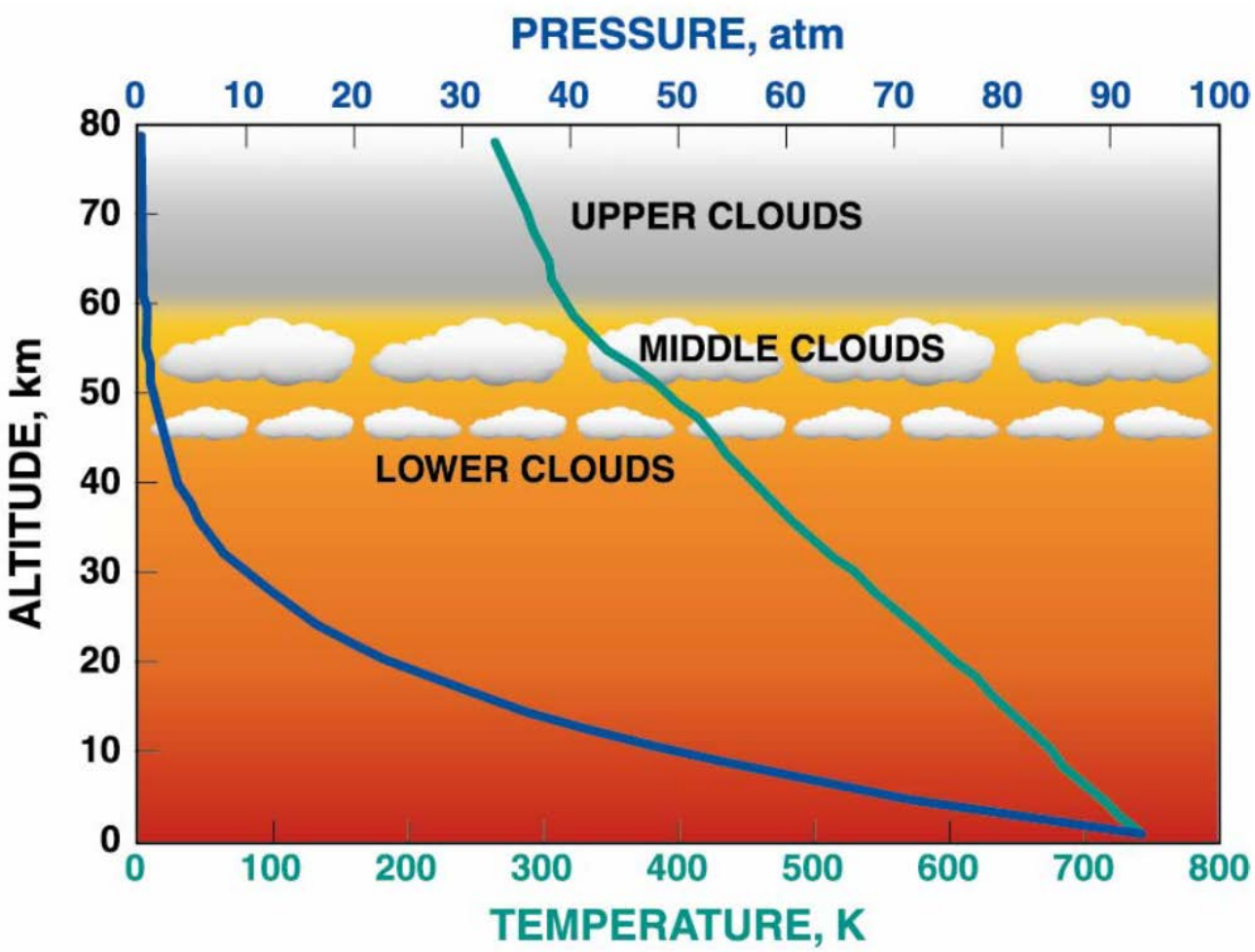
- Instrumentation for probes and aerial platforms
- Instrumentation for landed platforms

Mission Architectures

- Orbiters, probes, landers and aerial platforms
- Interoperability of communications

The challenge is to develop subsystem technologies that can tolerate and function in the severe environment of Venus

Extreme Environments on Venus



Extreme Environments on Venus

- Temperature regimes
  - Upper cloud region - -50° to +50° C
  - Below the clouds 200° to 300°C
  - Surface – 465° to 390°C

- Thick atmosphere
  - High surface pressure – 100 bars equivalent to 3000 kg of seawater
  - Blockage of EM radiation from gamma rays to radio waves

- Chemistry
  - Clouds - Sulfuric acid
  - Surface region - Supercritical fluid

- The maturity of technologies for operation in the Venus environment has been designated by a color code following NASA's Venus Technology plan

Mature. Ready for flight

High. Limited R&T and testing needed.

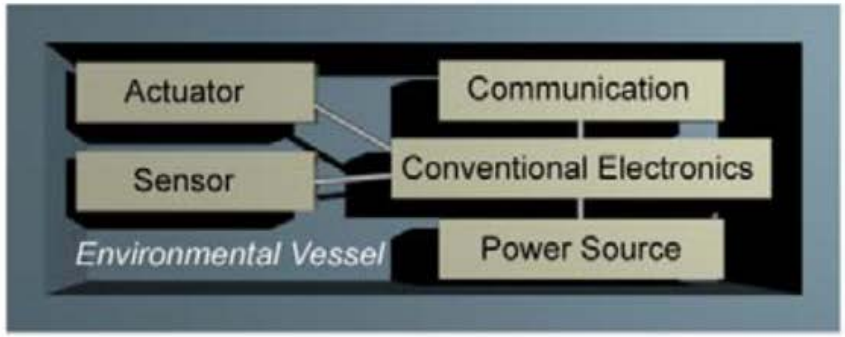
Moderate. Major R&D effort needed

Low. Large high risk R&D effort needed

Hybrid Systems for Extreme Environments

Protection Systems

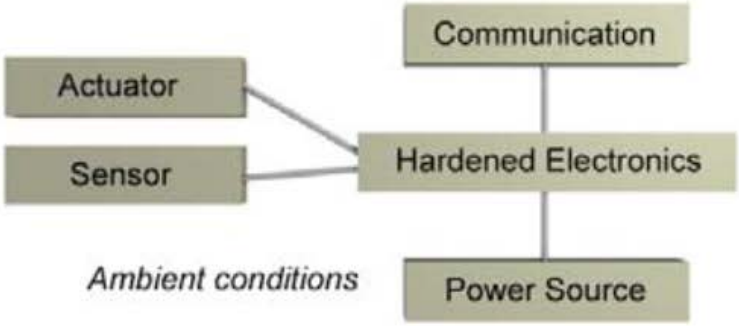
Use conventional components; Develop protection systems (Thermal vessel; pressure vessel, radiation shielding etc.)



Impractical for planned missions

Component Hardening

Develop technologies tolerant of extreme environments



Prohibitively expensive for some technologies

Hybrid Architecture

Combination of hardened components and environmental protection

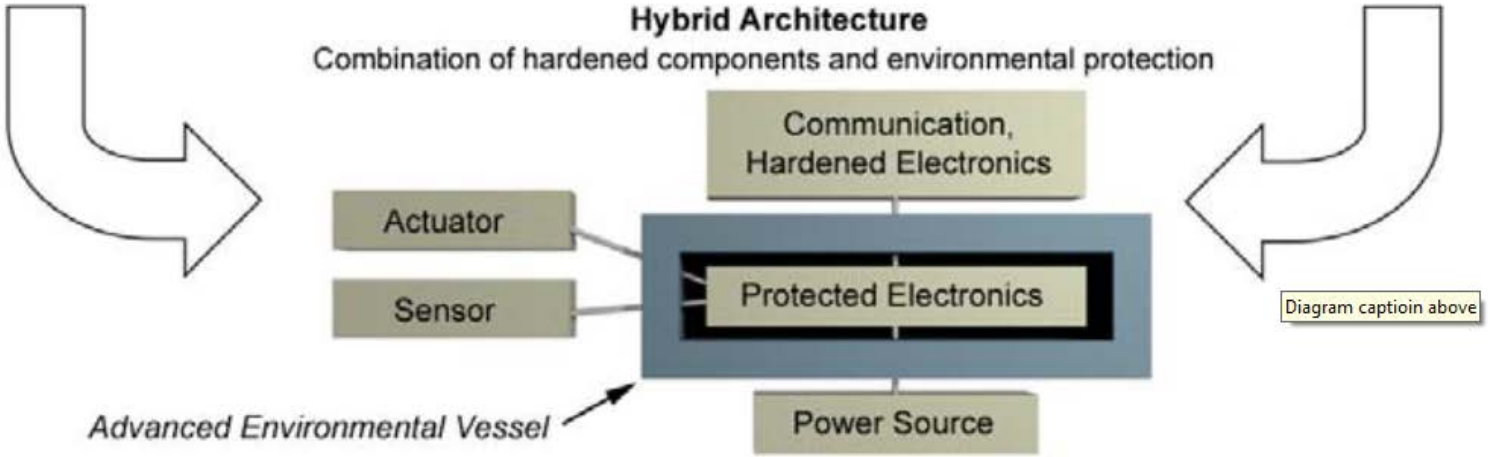


Diagram captioin above

Requires development of innovative architectures

What makes high temperatures so challenging?

- High temperatures accelerate the rate of physical and chemical processes in a manner that degrade the performance of many engineering systems used in planetary exploration

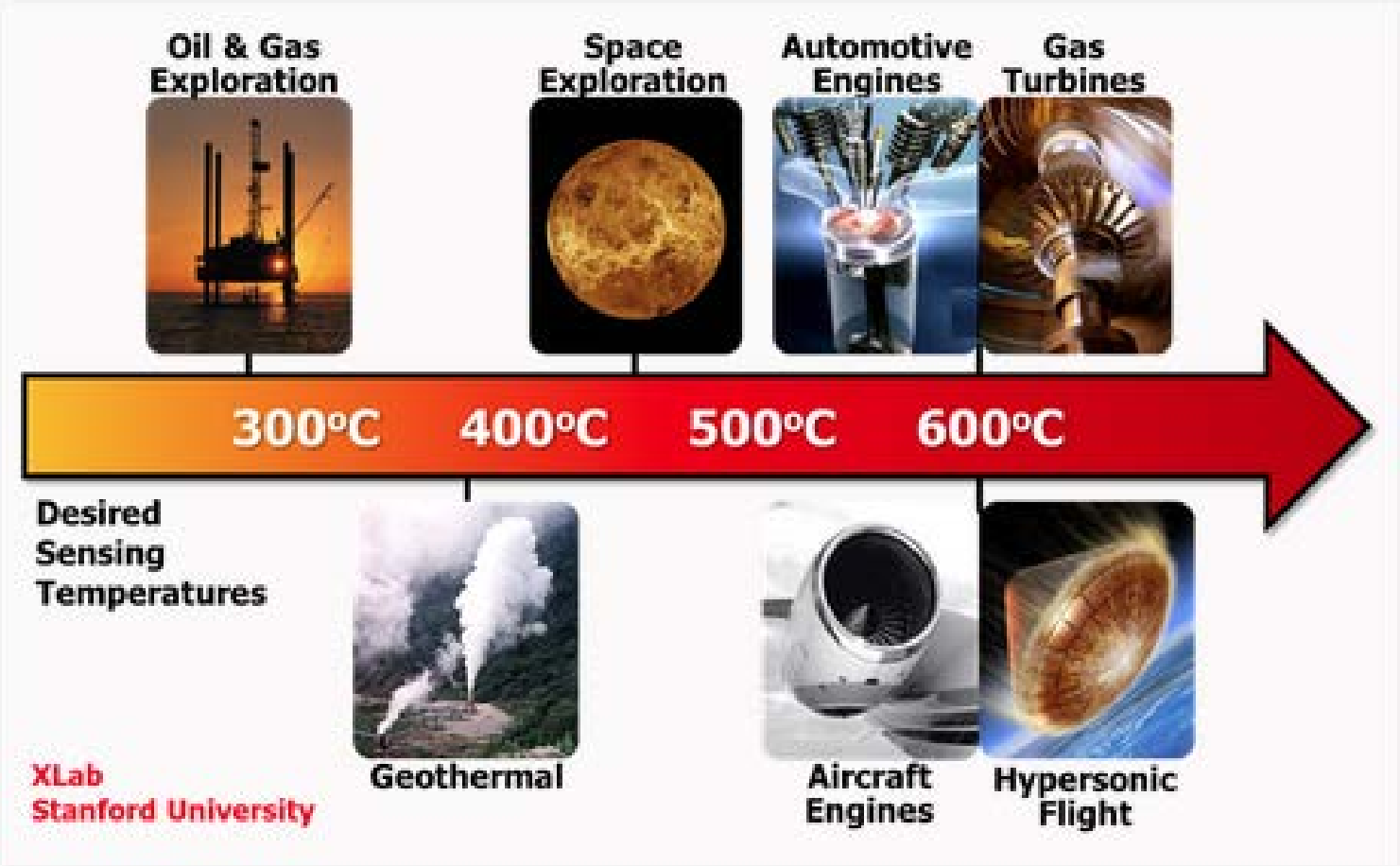
- The Arrhenius law quantifies this effect:

$k = Ae^{-E_a/(k_B T)}$	For physicists and electrical engineers
$k = Ae^{-E_a/(RT)}$	For chemist and mechanical engineers
E_a	Activation Energy - Volts
k_B	Boltzmann Constant 1.38 X 10^{-23} J/K.
T	Temperature (Kelvin)
k	Rate constant for chemical or physical process

- At room temperature $k_B T$ = 1/40 eV. At the Venus surface it is 2.5 times that

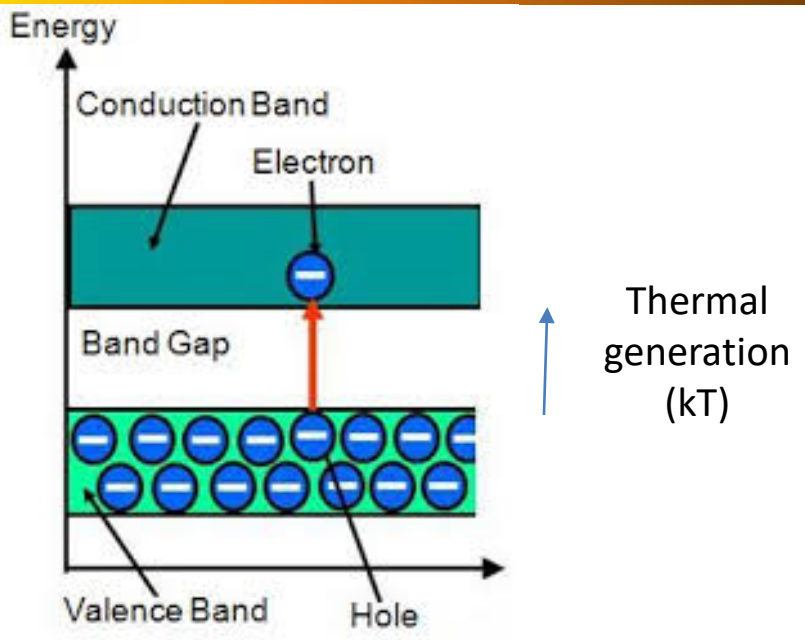
- This has a profound influence on the performance of
  - Electronics and optoelectronics – analog amplifiers, digital circuits, optical detectors, lasers
  - Batteries and photovoltaic arrays
  - Vacuum seals and material integrity

Electronics for High Temperatures - Drivers



Exploring Venus is not the only driver for the development of high temperature electronics – fortunately!

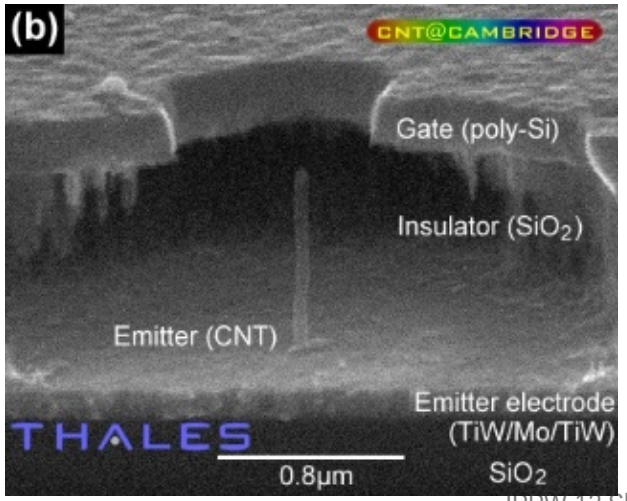
Electronics for high temperatures - Approaches



Comparison of Band Gap energy of semiconductor materials

Si-C polymorphs

Vacuum electronic devices with carbon nanotube (CNT) field-emitters of electrons



- **Large Band Gap Semiconductors*:** Materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN) have much lower thermal leakage at high temperatures than conventional materials (Silicon (Si) and Gallium Arsenide (GaAs))

- **Vacuum Electronics:** Devices using electrons flowing in vacuum are less sensitive to temperature than semiconductors- but can they be miniaturized?

***SiC and GaN also have potential as photovoltaic materials for generating power on Venus**

Medium Temperatures Semiconductor Electronics (300°C)

Silicon on Insulator (SOI) Parts

- Commercial parts are now available from Honeywell which operate at 300°C for extended periods

Standard Catalog Products:

- Operational Amplifier
- Voltage Regulators
- 8-bit Micro Controller

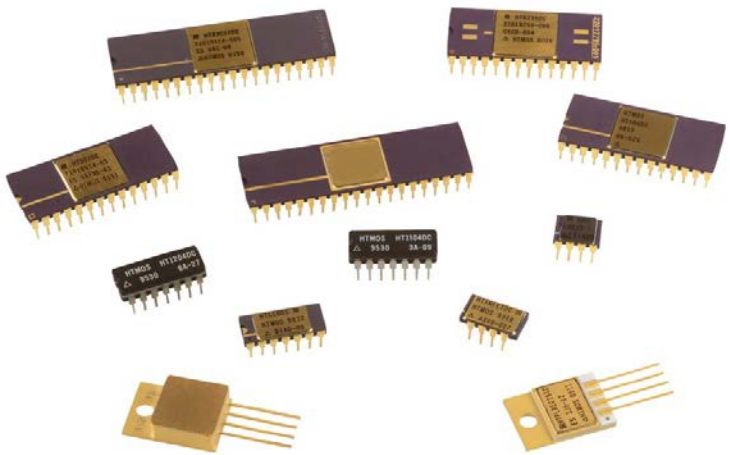
Custom Capabilities:

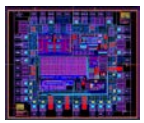
- Gate Arrays
- MCM (Multi-Chip Modules)
- High Temperature Design Services

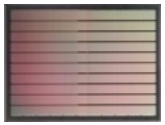
Products in Development (2009):

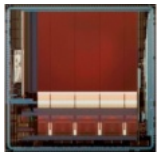
- HTA/D Converter (12 and 18 bit)
- HTEEPROM
- HTFPGA
- Reconfigurable Processor for Data Acquisition (RPDA)

2 Million Device Hours Worth Of Life Test Data







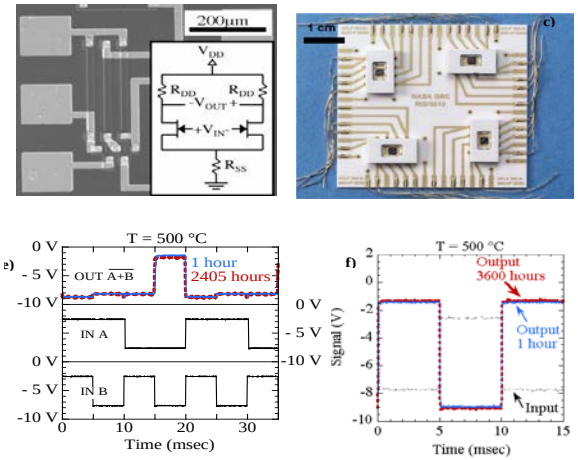


(Courtesy of Dewey Benson, Honeywell)

High Temperature Semiconductors Electronics (500°C)

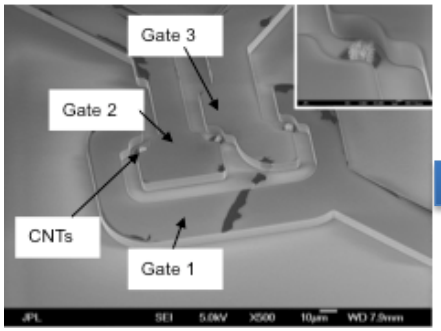
- Basic electronic components (Logic Gates, Ring Oscillators and Amplifier) operational
  - Silicon carbide electronics demonstrated with longer term operation (thousand of hours at 500°C)
- Level of complexity closer to the early formation of silicon electronics, e.g., Mercury era electronics
- Other activities ongoing in gallium nitride, diamond, and vacuum tubes (shorter duration)
  - GaN HEMT devices with pinch off less than 2V have been demonstrated at 500°C
- More advanced circuits under development with increased complexity (basic A/D, D/A, Flip-Flops, Multiplexers, Memory, etc.)
- Substrates, passive components and integration techniques require development

Basic High Temperature SiC Electronic Components (Extended 500°C operation)

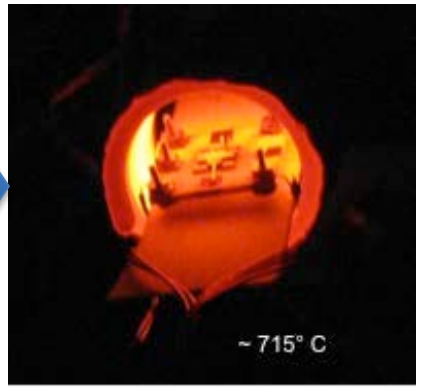


Vacuum Electronics including use of CNT cathodes

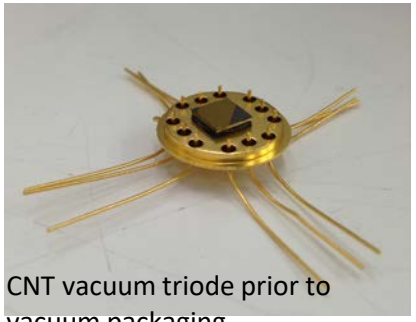
- Carbon nanotubes as field emitters and “digital” electronic components and analog electronic components have been demonstrated.
- Programmable logic gates have been demonstrated with DC switching at 700 C.
- The device density and switching speeds are projected to be comparable those of solid-state counterparts.
- Additionally chip-scale vacuum packaging is being adapted to produce analog CNT vacuum electronic components (diodes and triodes).



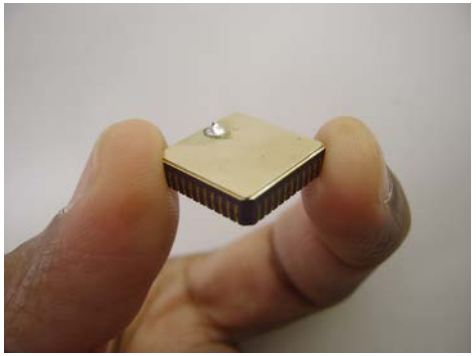
Programmable vacuum electronic logic gate (IMG)



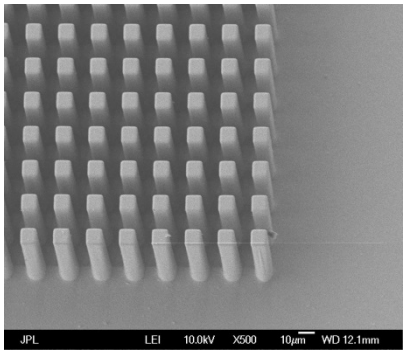
IMG under high temperature switching test



CNT vacuum triode prior to vacuum packaging



Chip-scale vacuum packaging: can withstand up to 350 C.



Micromachined capacitor (~200 nF) (demonstrated at 200 C)

Diffusion a challenge for vacuum devices

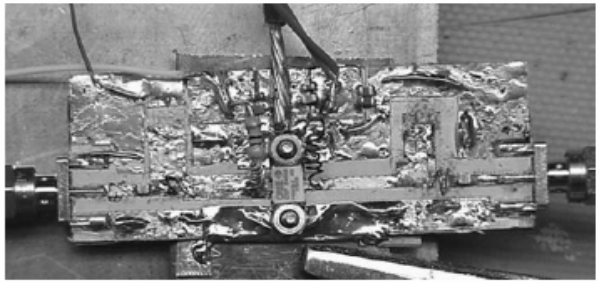
- Maintaining a vacuum at high temperatures and pressures also runs into Arrhenius law
- The smallest molecule helium which is present in the Venus atmosphere is the biggest challenge
- Pressure vessel will need to be of metal construction. Insulating elements are TBD

Diffusion of gases through materials at high temperatures

Material	Typical Helium permeation rate ($cm^3(STP)/s/cm^2$)	Typical time for critical rise in pressure
Glass	~1e-9	~seconds
Ceramic	~1e-14	~days
Metals	~1e-21	~decades

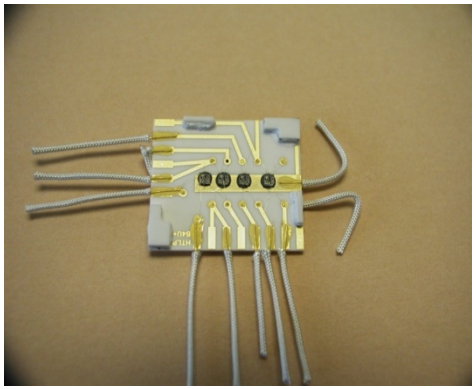
Communications at 500ºC: Solutions may involve combinations of semiconductor and vacuum components

- Passive RFID Systems operational at higher temperatures, e.g., up to 900°C; Simple measurement capability such as temperature with no data processing
- Wireless (and wired) data transmission demonstrated at near 500°C with limited data processing
  - Example: Over 2 m data transmission demonstrated for 24 days at circuit temperatures of 475°C associated with operation of a basic seismometer mechanism
- High power, high-frequency transmission with high temperature components, orbiter, significant technical challenge



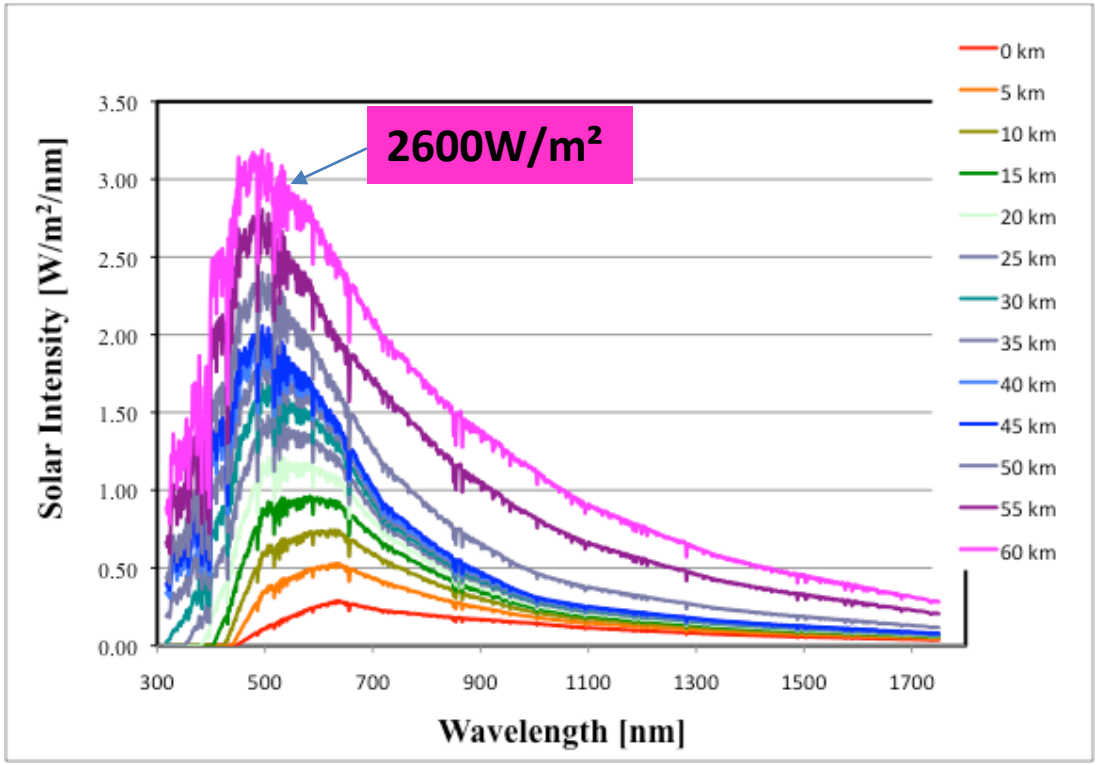
High Temperature SiC RF Amplifier Prototype (Softronics)

High temperature vacuum triode including heater, cathode, grid, and anode



High Temperature Wireless Resonator Unit

Imaging and Solar Power Generation at Venus

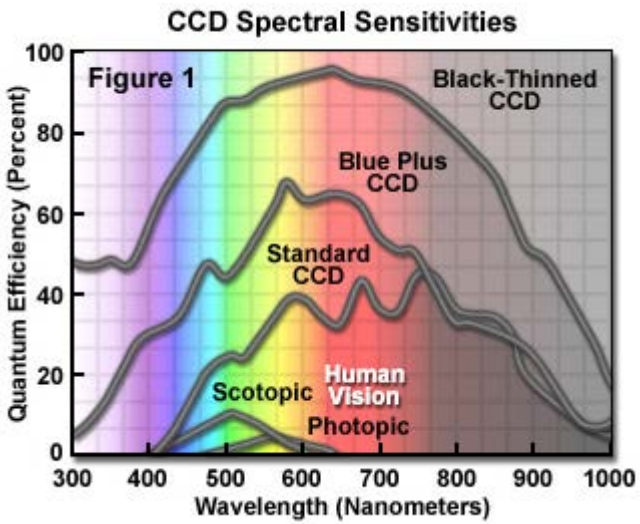


- Atmospheric scattering and absorption sharply limits the flux of radiation to the surface of Venus
- Below 10 km, the flux peaks in the red with little radiation at wavelengths shorter than 0.5 um
- This poses challenges for both imaging and power generation

A. L. Geoffrey et al. Analysis of Solar Cell Efficiency for Venus Atmosphere and Surface Missions. *11th IECEC*, AIAA (2013).

Imaging of the surface of Venus with sensors at Venus temperatures

Conventional **silicon charge coupled devices (CCDs)** cover a broad spectral range but have huge leakage currents at Venus surface temperatures



Silicon -carbide diodes can operate at 300°C with 10^{-6} of the dark current of a silicon diode. However they cut off in the violet where very little light reaches the Venus surface

Possible solutions – illuminate the surface with UV light. Acoustic imaging?

Energy Generation - Solar

Upper Atmosphere down to 30 km

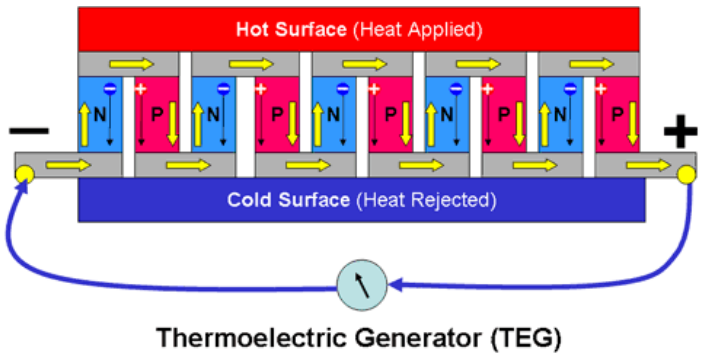
- Moderate to Temperatures – Moderate light levels
- Balloons can use standard triple junction cells should work encapsulated to tolerate sulfuric acid environment
- Long lived aircraft also require high specific power panels encapsulated to survive the sulfuric acid environment

Lower Atmosphere and Surface

- High temperatures to 460C, very low light levels
- Require new photovoltaic materials with low efficiencies under these conditions (GaN and SiC)

- Large array areas needed to generate useful power
- Requires a major technology development effort.

Thermoelectric Power Generation



Dimensionless Thermoelectric Figure of Merit, ZT

$$ZT = \frac{\sigma S^2 T}{\lambda} = \frac{S^2 T}{\rho \lambda}$$

Seebeck coefficient, S

Electrical conductivity, σ

Electrical resistivity, ρ

Thermal conductivity, λ

Absolute temperature, T

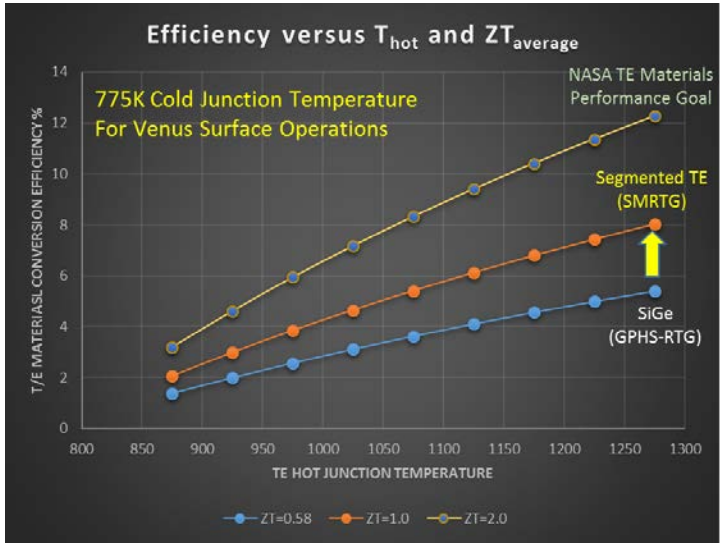
Conversion Efficiency

Carnot

Conversion Material Performance

$$\eta_{max} = \frac{T_{hot} - T_{cold}}{T_{hot}} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_{cold}}{T_{hot}}}$$

ΔT



Conversion efficiency is a direct function of ZT and ΔT
Generator efficiencies of 7% should be achievable on the Venus surface and higher as the vehicle rises in the atmosphere

Energy Storage - Batteries

- Primary Batteries – (-50<T<100C)
  - Needed to power short lived landers (a few hours)
  - Also needed for moderate duration balloons (2 weeks or less)
  - Improvements in specific energy will be mission enhancing

- Rechargeable batteries (>450C)
  - Rechargeable batteries to operate at Venus temperatures do not exist and may require entirely new technologies

- Primary batteries (>450C)
  - Batteries that release their energy at ~500C exist and might in principle be adapted for Venus applications

Passive Thermal Control

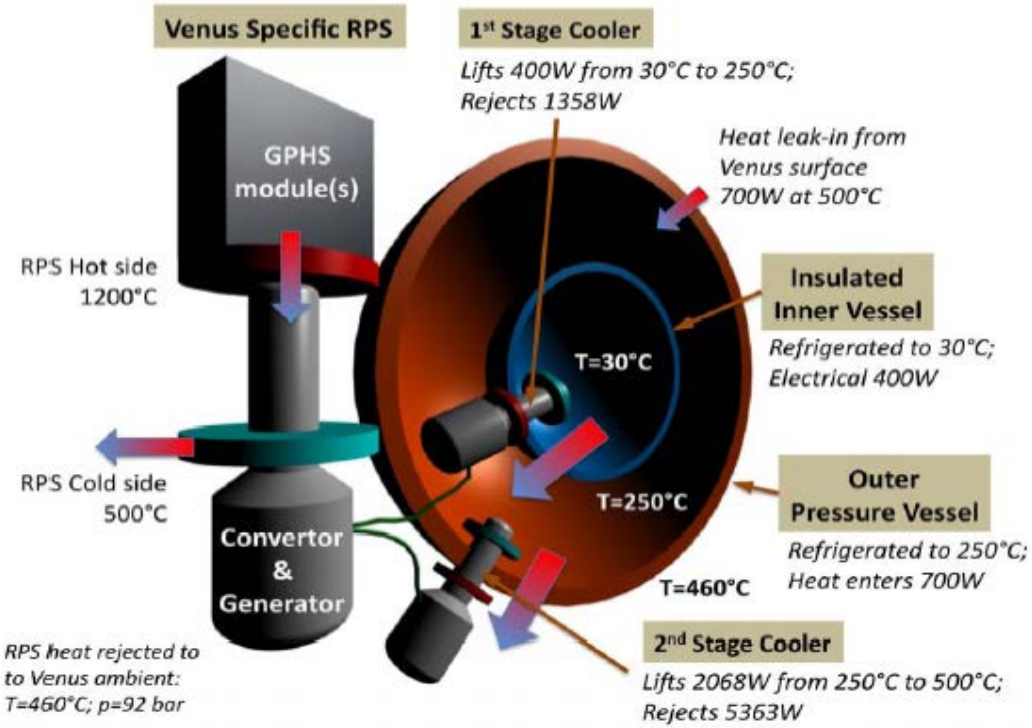
- Existing passive thermal control techniques are sufficient for Venus orbiters, atmospheric vehicles, and short lived probes and landers (5 hours)

- Several passive approaches have been explored to allow extension of the lifetime of a pressurized surface lander to 10 hours. These approaches need to be proven and tested

- Long lived landers will require hybrid systems either active cooling, as well as the used of components that operate at Venus temperatures and pressures.
  – Some limited purpose landers may use high temperature components alone

RPS-Based Power/Cooling

- To maintain payload elements at near earth ambient temperature requires a heat pump that can pump (extract) both the heat dissipated by the cooled systems and leaking in from the environment and reject them at Venus ambient
- A system in which both the power generation and the pump use an efficient mechanical Stirling cycle device. These converters are being developed for RPS application at NASA Glenn Research Center



Heating and Cooling Load	# Cooling Stages	# GPHS Required
Case 1: Complete Lander (400 W Heating/700 W Cooling)	1	94
	2	72
	3	54
Case 2: Lander Subset (100W Heating/700 W Cooling)	1	65
	2	31
	3	17

This system as specified is too large to be practical. Can dissipation and heat leaks be reduced so that practical systems are possible?

Mechanisms for high temperature operation

- High temperature mechanisms for surface missions will require development.
  - Motors exist today that have operated for long periods at Venus surface temperatures
    - However for feedback systems would require development of high-temp encoder systems

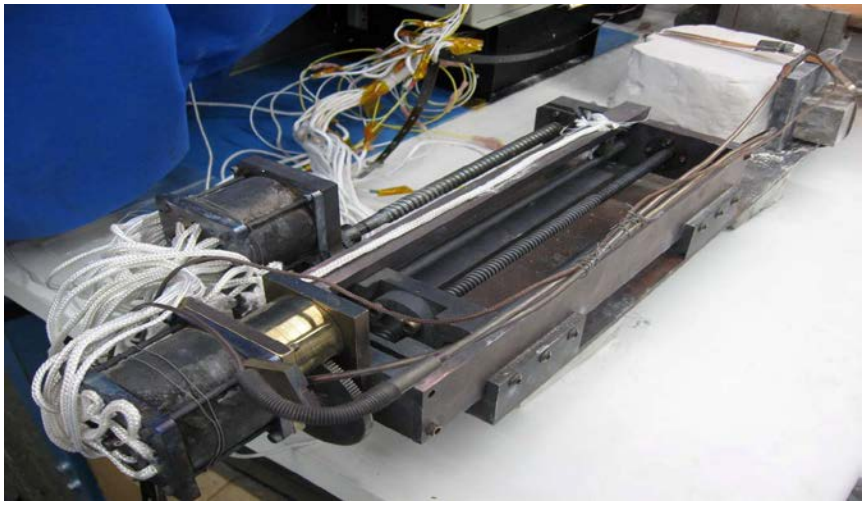
- Many mechanism components, materials, lubricants, etc… have been developed for operation at Venus temperatures, but testing and qualification for the Venus environment, especially at the system level is needed.

- Venus simulation facilities capable of this task are now coming online at NASA GRC

Brushless High-temperature DC motor (Honeybee)

Mechanisms

- Sample handling and caching techniques need to be tested with the mechanisms and instruments in Venus environment, this includes the algorithms for control and various faults conditions



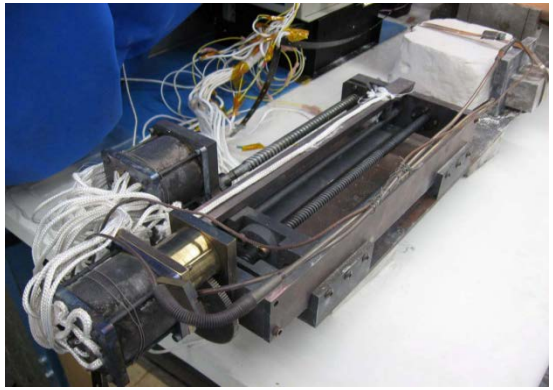
High Temperature Actuation and Motors

- Motors, drills and actuators are needed that are capable of operating at Venus temperatures. A ranges of systems have been demonstrated
  - A switched reluctance motor
  - Brushless DC Motors

- High temperature drills have also been developed

Switched-Reluctance Motor: 8,000 rpm at 540° C (NASA GRC)

Brushless High-temperature DC motor (Honeybee)



High-temperature drill

Guidance Navigation and Control (GN&C) Needs)

- Aerial platforms need accurate measurements of vehicle position, velocity and attitude. This is needed to
  - Permit precise determination of vehicle position to correlate with orbital observations
  - Enable high gain communications from the moving platform

- Landed platforms needs advanced GN&C technologies for
  - Precision landing
  - Attitude knowledge for high gain communications after landing

- Advances in GN&C technologies may also enable new scientific measurements related to Venus rotation and atmospheric circulation – e.g. characterization of gravity waves

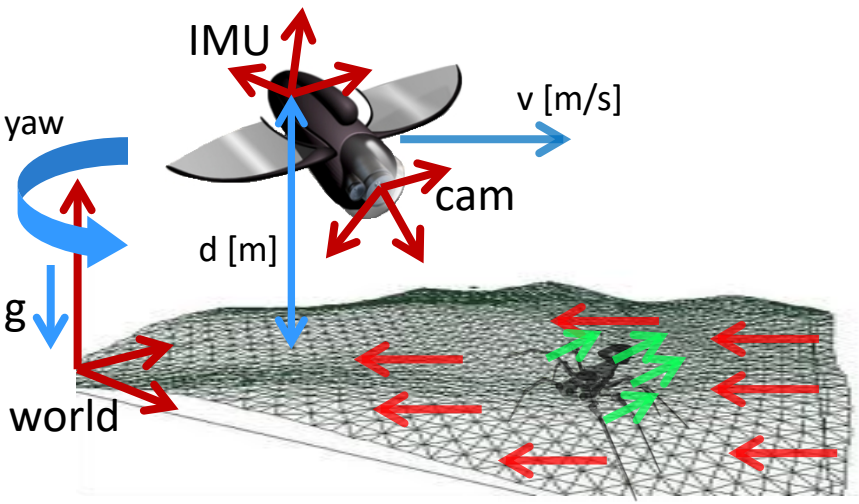
Vision-based attitude and velocity determination

- Advances in vision- based navigation for microaerial vehicles are enabling extremely fast and low power systems for determining
  - Attitude
  - Velocity

- Systems require only a camera and an IMU and may soon require the processor power of a PDA

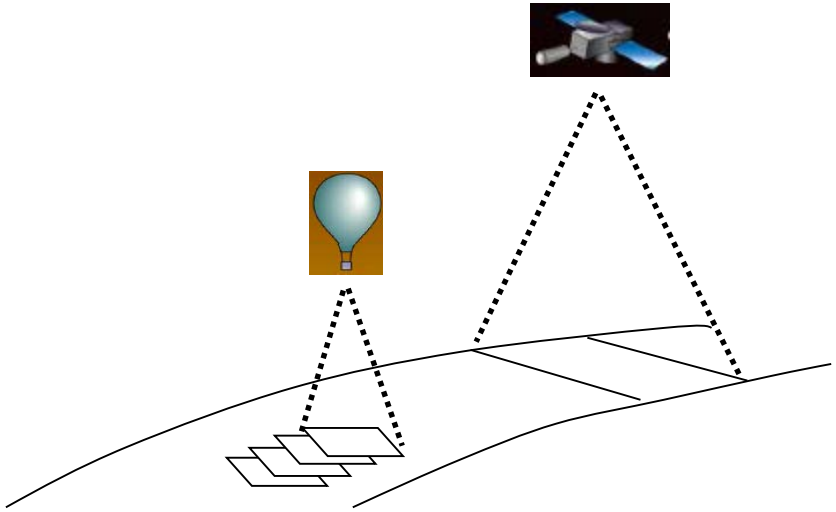
- For Venus and infrared camera would be needed to image surface features

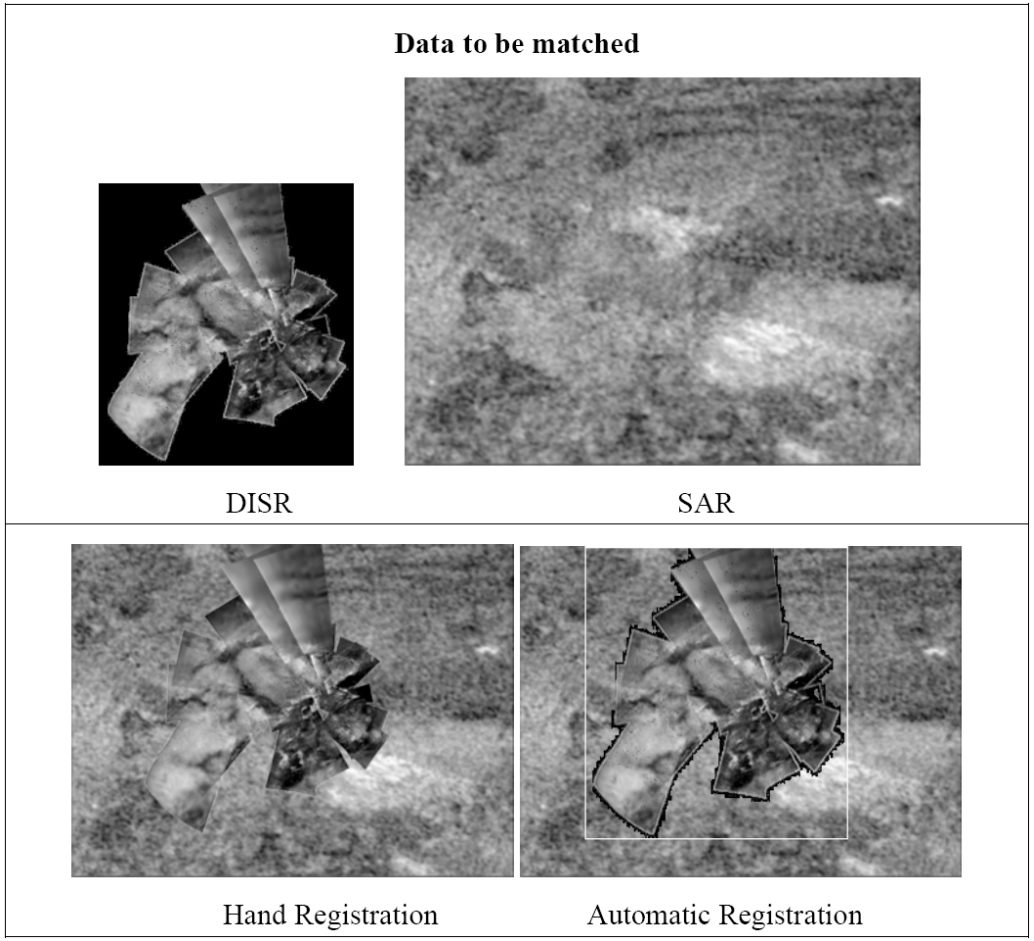
Guidance Navigation and Control for a Micro Aerial Vehicle or Precision Lander



Guidance, Navigation and Control
Localization with disparate data sets

A radar map obtained from orbital images is used to localize an aerial vehicle or a descending lander by correlating with visible or infrared images obtained with the in situ vehicle



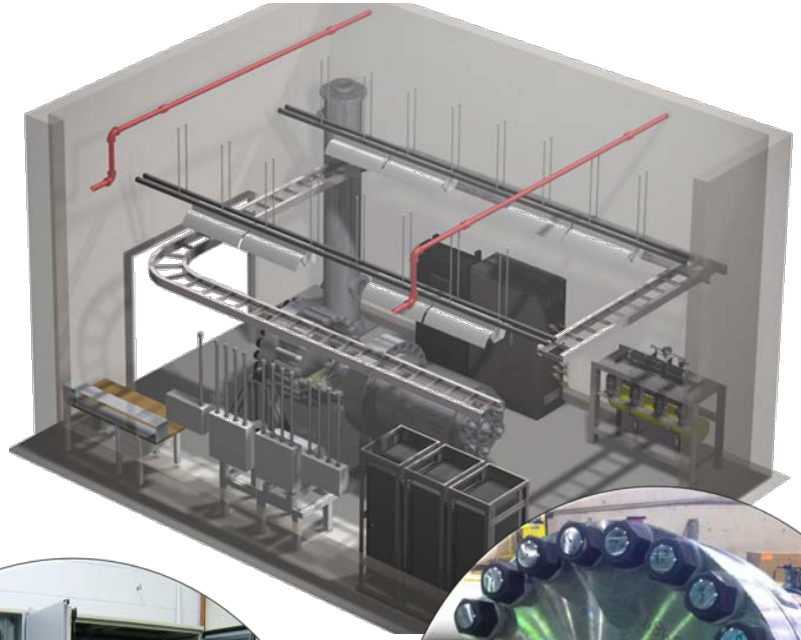


Test Facilities –Glenn Extreme Environments Rig (GEER)

Supporting science and technology testing in high temperature, high pressure, cryogenic, and vacuum environments with time accurate, parts per billion atmospheric mixing

- Unique chamber developed for up to 1500 PSI and 500°C full atmospheric testing

- Any atmosphere
- Vacuum & Cryo
- Dynamic PPB accuracy
- Science
- Technology Development0



Summary

- Extreme environments encountered at Venus have a profound influence on future approaches to exploring Venus.

- The subsystem technology for extended operations (beyond 1 day) on the surface of Venus or in the near surface environment is very difficult. Only very limited capabilities targeted will be practical for the foreseeable future

- The subsystem technology for extended operation by aerial platforms is more accessible. Electronics systems capable of operating below the clouds are already available. As time goes on it will be possible to extend operations closer to the surface

- Miniaturization in conventional electronic technologies can play a key role in the development of guided sondes that survive for brief periods on the Venus surface and return data to an aerial platform or orbiter for relay to Earth

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