Exploring Venus

Geoffrey A. Landis

With a temperature higher than the inside of your oven and atmospheric pressure equal to that a kilometer under the ocean, the surface of Venus is one of the most hostile environments in the solar system, and Venus exploration presents a challenge to technology. This lecture presents mission trade-offs and discusses a proposed mission concept for rover and aircraft based exploration of the surface and atmosphere of Venus. Several approaches to the technology, electronics, mechanical parts, and power systems, are discussed.
Venus: Earth's near-twin
Rocky planets- size comparison

Mercury  Venus  Earth  Mars
Venus: A Challenge for Exploration

- Solar day 117 days
- Surface temperature 452 C (850F)
  - Tops of mountains are slightly cooler: at the top of Maxwell Montes (10.4 km above mean elevation), temperature is “only” 390 C (725 F)
- Surface pressure 92 bars (equals pressure 1-km under the ocean) carbon dioxide
- Clouds are concentrated sulfuric acid droplets

Venus Exploration is a tough challenge!
Previous missions: Pioneer Venus (NASA)

- Pioneer Venus mission: four atmospheric probes plus orbiter (1978)
Previous Missions: Venera (Russian)
The Surface of Venus
First pictures from the surface from Russian “Venera” landers

Venera-9 image

Venera-10 image
Venera-14 images
The Surface of Venus
seen from the Russian “Venera” Venus landers

Venera-13 image

- Venera probes survived on surface for under 2 hours before failure
Previous Missions: VEGA (Russia):
ballooning in the Venus atmosphere
2 balloons floated for 48 hours at 54 km altitude
delivered by Halley's comet probe during Venus swingby

Russian VEGA balloon
ESA “Venus Express” orbiter
arrived in Venus orbit 2006
Future Venus Exploration?

- Atmospheric exploration
- Surface exploration
- Venus surface sample return
Goal: Science Driven Exploration

Science Questions: Geology

- What process resurfaced the planet in the (geologically recent) past?
- Why doesn’t Venus have plate tectonics like Earth?
- Does Venus have active volcanoes?
- Is the interior of Venus similar to the Earth?
- What is the “snow” deposits on the top of Venusian mountains?
- How does the sulfur in the atmosphere interact with the rock?
Goal: **Science Driven Exploration**

*Science questions: Atmosphere and Climate*

- **Venus is the greenhouse planet**: understanding the climate of Venus will teach us about the (past and future) climate of the Earth
- Understand planetary atmospheres by the process of comparison
- What causes the atmospheric super-rotation?
- What are the aerosol particles?
- What was Venus like in the early solar system? How did it lose its hydrogen?
Goal: **Science-driven Exploration**

**Science Questions: Astrobiology**

- Did Venus ever have an ocean? Did it once have life?
- What is the history of the chemical evolution of the Venus atmosphere? What can it tell us about the possibility of life starting on earthlike planets?
- Atmosphere of Venus has unexplained deviations from equilibrium: could this be signs of present day life?

(ref: Grinspoon 1997; Sattler *et al* 2001, Schulze-Makuch 2002)
Mission Goal:
Exploring Venus from the surface and the atmosphere

cool upper atmosphere

hot lower atmosphere

very hot surface
Venus Surface Exploration is highly challenging

- Russian Venera probes lasted less than two hours on the surface of Venus
- One American Pioneer probe made it to the surface and survived about an hour
- Extremely hostile environment!

but

- Scientifically interesting environment
Venus Surface Exploration:
New Technology Required

- **Electronics** needed to operate at 450+ C
- **Computers** needed to operate 450+ C
- **Power System** needed to operate at 450+ C
- **Mechanical components** to operate at 450+ C
Science mission for Venus Surface Rover

• Characterize the surface at geologically diverse locations
• Emplace seismometers to determine the interior structure
Venus Surface Rover

The surface mission is to characterize the surface of Venus at a level of detail comparable to that of the Mars Exploration Rovers (MER) mission.

Mission criteria:
1. Mission duration on surface: 50 (Earth) days.
2. Mobility requirement: 600 meters minimum.
3. Multiple landing sites with geological diversity.

The science mission of the Venus surface rovers is to examine the surface at the local scale, measuring the chemistry and diversity of rocks and determining the interaction of the atmospheric chemistry with the rock mineralogy. The rover also emplace multiple seismometers to determine the interior structure of Venus, answer the thick crust/thin crust model question, and search for present-day tectonic activity and volcanism.
Electronics for surface operation: trade-off study

- **Approach 1**: Rover electronics capable of operating at surface temperature of 460°C
  - 460°C electronics is being developed, based on SiC material
Electronics for surface operation: trade-off study

• 500°C electronics being developed, based on SiC
  • Transistors demonstrated to operate at 500 C
    • SiC transistors have been made and operated at Venus temperatures
    • Thousands of hours at temperature now demonstrated
    • First integrated circuit: SiC op amp
    • Demo radio receiver in progress

• Cameras and sensors: more difficult, but could be constructed
  (conceptual camera design uses scanned GaP photodiodes)

  • http://www.grc.nasa.gov/WWW/RT/2005/RI/RIS-neudeck2.html
Electrical Operation of 6H-SiC MESFET at 500 °C for 500 Hours in Air Ambient

David Spry¹, Philip Neudeck², Robert Okojie², Liang-Yu Chen¹, Glenn Beheim², Roger Meredith², Wolfgang Mueller³, and Terry Ferrier²

¹OAI, Cleveland, OH
²NASA Glenn Research Center, Cleveland, OH
³Research 2000, Inc. Cleveland, OH

Abstract

A high temperature n-channel 6H-SiC metal semiconductor field effect transistor (MESFET) was fabricated, packaged, and electrically operated continuously at 500 °C for over 500 hours in an air ambient with less than 10% change in operational transistor parameters. To the best of our knowledge, this is the first report of a semiconductor transistor operating in this harsh environment with excellent stability over an extended period of time. The fabrication process that enabled such stability in air atmosphere featured multiple levels of high temperature metal and dielectric passivation to prevent contamination (particularly oxygen) from reaching electrically sensitive interfaces. A thick-film metallization based ceramic package with conductive die attach material and Au wire bonds facilitated long-term testing under electrical bias at 500 °C. Over the course of the 500 hour operational test in air, the only observed degradation of transistor characteristics was increased leakage of the gate-channel diode as anneal time increased. This demonstration of 500 °C transistor durability represents an important step toward significantly expanding the operational envelope of sensor signal processing electronics for harsh combustion-engine environments.
Electronics for surface operation: trade-off study

- **Approach 1**: Rover electronics capable of operating at surface temperature of 460°C
  - 460°C electronics is being developed, based on SiC materials

- Microprocessor: highest-temperature existing microprocessor operates at 300°C

- **Microelectronics for Venus Surface Conditions not yet ready**

- Conclusion:
  - Some parts are ready, but whole mission cannot be done with available parts
  - Integrated circuits and computers are farther in the future
Electronics for surface operation: trade-off study

• **Approach 1**: Rover electronics capable of operating at surface temperature of 460°C
  – 460°C electronics is being developed
  – Not available today
  – Integrated circuits and computers are farther in the future

• **Approach 2**: Refrigerator to keep electronics at low temperature
  – Requires power and moving parts
  – Allows existing electronics
These microcontrollers provide guaranteed performance supporting operating frequencies in excess of 16 MHz over the full -55 to +225°C temperature range. Typically, parts will operate up to +300°C for a year, with derated performance. All parts are burned in at 250°C to eliminate infant mortality.
Venus Surface cooling system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Stirling cycle</td>
</tr>
<tr>
<td>Stages</td>
<td>1</td>
</tr>
<tr>
<td>Heat sink temperature</td>
<td>500 °C</td>
</tr>
<tr>
<td>Cold temperature</td>
<td>200 ºC</td>
</tr>
<tr>
<td>Heat transferred</td>
<td>105.7 W</td>
</tr>
<tr>
<td>Heat rejected</td>
<td>344.6 W</td>
</tr>
<tr>
<td>Overall coefficient of</td>
<td>37.6%</td>
</tr>
<tr>
<td>performance</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>1.6 kg</td>
</tr>
</tbody>
</table>
Sterling cooler design
Atmospheric temperature decreases with altitude
Electronics for surface operation: trade-off study

• **Approach 1:** Rover electronics capable of operating at surface temperature of 460°C
  - 460°C electronics is being developed
  - Not available today
  - Integrated circuits and computers are farther in the future

• **Approach 2:** Refrigerator to keep electronics at low temperature
  - Requires power and moving parts
  - Allows existing electronics

• **Approach 3:** Some rover electronics operating at 460°C, but computer is overhead in cooler atmosphere
  - More complicated
  - Allows use of electronics available today
Robotic Exploration Concept:
"brains" of the robot stay in the cool middle atmosphere

- Computer stays in cooler middle atmosphere
- Surface robot uses simple high-temperature electronics
- Aerostat vs. airplane trade study indicates airplane is preferable

Surface exploration robots controlled by remote computer

Communications satellite relays to Earth

Control & computer system in airplane
Animation is available at:
http://www.grc.nasa.gov/WWW/5000/pep/photo-space/venus-mission-design.htm

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Venus surface

- Venera 9: The size of most rocks was estimated to be around 50-70 centimeters and the height 15-20 centimeters.

- Venera 14: landing site was a smooth plain
Rover concept
Rover landing concept

• Rover lands directly on parachute-- after the aeroshell is jettisoned, there is no separate "lander" vehicle

• High temperature parachute material such as glass-fiber cloth is required

• Due to thick atmosphere, parachute descent velocity is low (12 x less than parachute descent velocity on Earth)

  • Vehicle will sense transverse velocity relative to surface and rotate so that velocity is in direction of wheel rotation

  (note that surface winds are low)

• "Land on Wheels" technique is now baselined for 2009 MSR Mars rover, with similar vertical velocities.
Surface Rover concept

- Seismometer Deployment
- Wheel Deployment Parallelogram Concept
- 35cm Pressure Vessel
- Supporting Truss Work
- COMM
- Rock Abrasion Arm (Tool)
- X-Ray and Gamma Ray
- Cameras
- Radiators
- Un-pressurized Instruments (Place Holder)
- DIPS Power Supply
- Drive Motors
- Cameras

CAD model by Shawn Krizan, NASA LaRC

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Surface Rover dimensions

- CAD model by Shawn Krizan, NASA LaRC
Venus Rover packaged into aeroshell
Max Aeroshell Diameter = 2.0m
### Venus Surface Robot Technologies: motors and actuators

#### High temperature motors/actuators

<table>
<thead>
<tr>
<th>Motor or actuator</th>
<th>Max operating temperature (°C)</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baker Hughes GeoThermal</td>
<td>160</td>
<td>commercial</td>
</tr>
<tr>
<td>Swagelock pneumatic</td>
<td>200</td>
<td>commercial</td>
</tr>
<tr>
<td>Rockwell Scientific SiC</td>
<td>200</td>
<td>development project</td>
</tr>
<tr>
<td>NASA Glenn R&amp;T high-temperature actuator</td>
<td>400, 600</td>
<td>prototype goal; research target</td>
</tr>
<tr>
<td>NASA Glenn switched-reluctance motor</td>
<td>540</td>
<td>demonstrated; 8000 RPM, 27 hours</td>
</tr>
<tr>
<td>U. Sheffield Linear actuator</td>
<td>800</td>
<td>technology demonstrator: 1 mm throw, 500N force</td>
</tr>
<tr>
<td>NASA Glenn/MSU RAC smart materials: Shape memory alloy actuators</td>
<td>150, 500, 1000</td>
<td>Shape memory (SMA): commercial SMA: material demonstrated SMA: high temperature goal</td>
</tr>
<tr>
<td>NASA Glenn smart materials: piezoelectric</td>
<td>&gt;1000</td>
<td>Piezoelectric high temperature goal</td>
</tr>
</tbody>
</table>
Switched-reluctance motor capable of operation at 540 C

• Small version of this motor has now been demonstrated at Honeybee robotics
Power source

• *Approach 1*: Radioisotope Power source
• *Approach 2*: Solar power
• *Approach 3*: microwave beamed power
• *Approach 4*: Chemical energy conversion
Venus Surface power source

• **Approach 2: Solar power**
  - Low light levels and high temperature at surface
    - Existing solar cells work poorly at high temperature
    - New high-temperature solar technologies are most sensitive to blue light
  - Good solution for high-altitude aircraft (>50km)
  - High temperature solar-cell technology is improving
  - Approach not feasible on surface with today’s technology
Solar energy in the Venus atmosphere

- At surface, power available is 10% of exoatmospheric power at 1000 nm, <1% at 450 nm
Venus Surface power source

• **Approach 3: microwave beamed power**
  - Station in atmosphere produces solar power; power beamed to surface by microwaves
  - Many technical questions need to be answered
  - Used as backup approach
Venus Surface power source

• *Approach 4: Chemical power*

• **Battery or fuel cell**
  • Good for prime power for short mission
  • For long mission, storage of reactants needed becomes critical
  • Analyzed for power buffering for isotope power systems
Venus Surface power source selected

• *Approach 1: Radioisotope Power source*
  • Although 460°C is a higher heat rejection temperature than most dynamic conversion approaches, should be possible
  • Long history in planetary exploration
  • Dynamic or thermoelectric conversion approaches possible
• *Baseline technology chosen for the Venus rover*
Radioisotope power: thermoelectric conversion

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>thermoelectric</td>
</tr>
<tr>
<td>Power produced</td>
<td>30 Watts</td>
</tr>
<tr>
<td>T (source)</td>
<td>1077°C</td>
</tr>
<tr>
<td>T (sink)</td>
<td>600°C</td>
</tr>
<tr>
<td>Conv. efficiency</td>
<td>5%</td>
</tr>
<tr>
<td>Input Qh</td>
<td>594 W</td>
</tr>
<tr>
<td>Heat Rejected, Qr</td>
<td>564 W</td>
</tr>
</tbody>
</table>

- Thermoelectric converters similar to Cassini power system
- Advantage: no generator needed; high TRL
- Radiator area .075 square meters
- Possible approach for small power system
- Three units would be needed for 100 watts usable power
## Radioisotope Power: Sterling conversion

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Stirling cycle</td>
</tr>
<tr>
<td>Power output</td>
<td>478W</td>
</tr>
<tr>
<td>Source</td>
<td>7 250-W GPHS units</td>
</tr>
<tr>
<td>T (source)</td>
<td>1200 °C</td>
</tr>
<tr>
<td>T (sink)</td>
<td>500 °C</td>
</tr>
<tr>
<td>Heat input</td>
<td>1740 W</td>
</tr>
<tr>
<td>Heat rejected</td>
<td>1267 W</td>
</tr>
<tr>
<td>Overall efficiency</td>
<td>23.4%</td>
</tr>
<tr>
<td>Mass</td>
<td>21.6 kg</td>
</tr>
</tbody>
</table>
Stirling Radioisotope Power Converter
Venus airplane unfolding
Solar Airplane Figure of Merit

- 50-60 km above surface, Venus atmosphere density profile similar to Earth's
  - Airplane design can use Earth experience
- Gravity 90% of Earth's
  - Powered flight easier
- Above the clouds, Venus has more sunlight than Earth
  - Solar flight is easier on Venus than on Earth
- Acid droplets in atmosphere require all exposed surfaces be corrosion resistant
  - Avoid exposed metal surfaces.
  - All metal surfaces need passivation coating
  - Acid-resistant materials are well developed technology
Solar airplanes on Earth

Right: Aerovironment “Pathfinder”

Below: NASA Glenn solar airplane team
Venus wind

• To stay in constant sunlight, a solar-powered Venus airplane must fly faster than the high-altitude wind.
Comparison of energy needed to fly against wind versus solar availability

Stationkeeping possible but temperature too high

Power Required

Power Available

6 m
9 m
12 m
6 m
9 m
12 m

Stationkeeping possible
Venus airplane: revised design
Venus airplane folded into aeroshell
# Venus element mass summaries

## VENUS AIRPLANE MASS SUMMARY

<table>
<thead>
<tr>
<th>System Description</th>
<th>Mass Fraction</th>
<th>Mass (kg)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airplane</td>
<td>20%</td>
<td>103</td>
<td>NA</td>
</tr>
<tr>
<td>Heatshield Structure</td>
<td>7%</td>
<td>36.05</td>
<td>Pioneer</td>
</tr>
<tr>
<td>Heatshield TPS</td>
<td>13%</td>
<td>66.95</td>
<td>Pioneer</td>
</tr>
<tr>
<td>Backshell Structure (Gussets, Separation ftgs, Paint, Vent, etc)</td>
<td>12%</td>
<td>61.80</td>
<td>Pioneer</td>
</tr>
<tr>
<td>Backshell TPS</td>
<td>8%</td>
<td>41.20</td>
<td>Pioneer</td>
</tr>
<tr>
<td>Parachute System</td>
<td>10%</td>
<td>51.50</td>
<td>Pioneer</td>
</tr>
<tr>
<td>Airplane Deployment Mechanism (Separation from Backshell)</td>
<td>15%</td>
<td>77.25</td>
<td>Mars Airplane</td>
</tr>
<tr>
<td>Misc (COMM, Power, Ballast, etc)</td>
<td>15%</td>
<td>77.25</td>
<td>Mars Airplane</td>
</tr>
</tbody>
</table>

Total Entry Mass: 100.0%  660
Contingency Mass: 7.0%  46

Total With Contingency: 107.0%  706

NOTE: Mass Fractions Based off Venus Pioneer Large Probe

## VENUS ROVER MASS SUMMARY

<table>
<thead>
<tr>
<th>System Description</th>
<th>Mass Fraction</th>
<th>Mass (kg)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rover</td>
<td>50.0%</td>
<td>330</td>
<td>NA</td>
</tr>
<tr>
<td>Heatshield Structure</td>
<td>7.0%</td>
<td>46.20</td>
<td>Pioneer</td>
</tr>
<tr>
<td>Heatshield TPS</td>
<td>13.0%</td>
<td>85.80</td>
<td>Pioneer</td>
</tr>
<tr>
<td>Backshell Structure (Gussets, Separation ftgs, Paint, Vent, etc)</td>
<td>12.0%</td>
<td>79.20</td>
<td>Pioneer</td>
</tr>
<tr>
<td>Backshell TPS</td>
<td>8.0%</td>
<td>52.80</td>
<td>Pioneer</td>
</tr>
<tr>
<td>Parachute System</td>
<td>10.0%</td>
<td>66.00</td>
<td>Pioneer</td>
</tr>
<tr>
<td>Lander with Airbags</td>
<td>0.0%</td>
<td>0.00</td>
<td>Pioneer</td>
</tr>
<tr>
<td>Misc (COMM, Power, Ballast, etc)</td>
<td>0.0%</td>
<td>0.00</td>
<td>Pioneer</td>
</tr>
</tbody>
</table>

Total Entry Mass: 100.0%  660
Contingency Mass: 7.0%  46

Total With Contingency: 107.0%  706

Mass Fractions Based off Venus Pioneer Large Probe

## RCS System Description

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Quantity</th>
<th>Mass (kg)</th>
<th>Source</th>
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<tbody>
<tr>
<td>* Marquardt 100lbf Thruster</td>
<td>2</td>
<td>8.0</td>
<td>Historical Data</td>
</tr>
<tr>
<td>** Rockwell 25lbf Thruster</td>
<td>6</td>
<td>25.0</td>
<td>Historical Data</td>
</tr>
<tr>
<td>Fuel Tank</td>
<td>1.0</td>
<td>54.2</td>
<td>Historical Data</td>
</tr>
<tr>
<td>Oxidizer Tank</td>
<td>1.0</td>
<td>5.42</td>
<td>Historical Data</td>
</tr>
<tr>
<td>Pressurant Tank</td>
<td>1.0</td>
<td>3.62</td>
<td>Historical Data</td>
</tr>
<tr>
<td>Associated Hardware (Valves, fittings, line)</td>
<td>NA</td>
<td>4.345</td>
<td>Historical Data</td>
</tr>
<tr>
<td>Propellant/Pressurant</td>
<td>NA</td>
<td>103.9</td>
<td>NA</td>
</tr>
<tr>
<td>Fuel</td>
<td>45.4 liters</td>
<td>39.0</td>
<td>DV = 350m/s</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>45.0 liters</td>
<td>64.4</td>
<td>DV = 350m/s</td>
</tr>
<tr>
<td>Pressurant</td>
<td>NA</td>
<td>0.5</td>
<td>DV = 350m/s</td>
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</table>

Total RCS Wet Mass: 155.8

## Mass Summary

<table>
<thead>
<tr>
<th>Mass Summary</th>
<th>mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aeroshell Payload Package</td>
<td>670</td>
</tr>
<tr>
<td>RCS Dry Mass</td>
<td>51.9</td>
</tr>
<tr>
<td>RCS Propellant/Pressurant</td>
<td>103.9</td>
</tr>
<tr>
<td>Total Dry Mass</td>
<td>721</td>
</tr>
<tr>
<td>Total Wet Mass</td>
<td>825</td>
</tr>
</tbody>
</table>

* Marquardt R-4D-1/10 (Isp 300s, Vac Thrust = 444N, Fuel Biprop - N204/Hydrazine
** Rockwell (Rocketdyne) R-1E-3 Shuttle vernier, Isp = 225s, Vac Thrust 111N, Fuel Mono - Hydrazine
Conclusion:
Venus surface exploration is challenging… but possible

- High-temperature robots on surface
- Computer system in atmosphere
- Communications relay in orbit
- Capability similar to Mars rovers

*Surface and atmosphere exploration project sets the stage for a Venus sample return mission*
For More Details:

- Web page and movie

- Mission Design:

- Venus Airplane:

- Power and cooling systems:

- High-temperature electronics:
  - P. Neudeck, NASA Glenn Research & Technology 2005,
  - NASA/TM-2006-214096

- My home page http://www.sff.net/people/geoffrey.landis
- MIT page: mit.edu/aeroastro/www/people/landis/landis.html
High temperature Fuel Cells

Solid Electrolyte CO/O2 fuel cell

- Demonstrated on Earth
- Uses zirconia-based solid electrolyte developed for hydrogen fuel cells
- Reactant is available on Venus
- 500-600°C nominal operating temperature, slightly higher than Venus ambient
Stirling Cooler for the Venus Surface

NOTE: DIMENSIONS IN CM

EXPANSION SPACE

2.00 BEAT ACCEPTOR

12.100

8.00 BEGENERATOR

2.00 BEAT REJECTOR

28.800

COMPRESSION SPACE

Ø 4.400

DISPLACER CRANK ROTATION

Ø 1.100

PISTON CRANK ROTATION

CHAIN SPROCKET ON CRANKSHAFT

PISTON

DISPLACER