Summary for Oral Presentation/Viewgraphs:

Surprisingly little is known about Venus, our neighboring sister planet in the solar system, due to the challenges of operating in its extremely hot, corrosive, and dense environment. For example, after over two dozen missions to the planet, the longest-lived lander was the Soviet Venera 13, and it only survived two hours on the surface. Several conceptual Venus mission studies have been formulated in the past two decades proposing lander architectures that potentially extend lander lifetime. Most recently, the Venus Science and Technology Definition Team (STDT) was commissioned by NASA to study a Venus Flagship Mission potentially launching in the 2020-2025 time-frame; the reference lander of this study is designed to survive for only a few hours more than Venera 13 launched back in 1981!

Since Cytherean mission planners lack a viable approach to a long-lived surface architecture, specific scientific objectives outlined in the National Science Foundation Decadel Survey and Venus Exploration Advisory Group final report cannot be completed. These include: mapping the mineralogy and composition of the surface on a planetary scale; determining the age of various rock samples on Venus, searching for evidence of changes in interior dynamics (seismometry) and its impact on climate; and many other key observations that benefit with time scales of at least a full Venus day (i.e., daylight/night cycle).

This report reviews those studies and recommends a hybrid lander architecture that can survive for at least one Venus day (243 Earth days) by incorporating selective Stirling multi-stage active cooling and hybrid thermoacoustic power.
Long-Lived Venus Lander Conceptual Design: How To Keep It Cool

Rodger W. Dyson, Paul C. Schmitz,
L. Barry Penswick, Geoffrey A. Bruder
NASA Glenn Research Center
Cleveland, OH
Aug. 5, 2009

IECEC 2009 / Session 30-EC-7 / AIAA-2009-4631
Thermal Energy Conversion Technology and Applications
The Outstanding Mysteries of Venus

- **The Evolution of Venus**
  - Why did Venus evolve so differently from Earth?
  - Was there ever an ocean on Venus, and if so, when did it exist and how did it disappear?
  - Did conditions for life or life in some form ever exist on Venus?
  - Did Venus lose an early atmosphere to catastrophic loss?
  - Did Venus ever have plate tectonics?
  - What caused the extensive resurfacing of Venus during the last Gy?
  - Are the resurfacing and climate change somehow related?

- **Venus Today**
  - Is Venus currently geologically active?
  - Why is Venus' atmosphere super-rotating?
  - Why doesn't Venus have a magnetic field?
  - How does the upper atmosphere interact with space environment?
  - What absorbs sunlight in Venus' atmosphere?
  - Why does Venus rotate backwards and slowly?
  - How do the surface and atmosphere interact chemically?
Environments Encountered by In-Situ Elements

H = 70 km; T = 40°C; p = 3.7E-2 bar; v(mean) = 92 m/s

H = 52 km; T = 150°C; p = 0.8 bar; v(mean) = 61 m/s

H = 15 km; T = 348°C; p = 33 bar; v(mean) = 16 m/s

H = 0 km; T = 462°C; p = 92 bar; v(mean) = 0.6 m/s

̃96.5% CO₂, ̃3.5% N₂, Trace SO₂, ⁴⁰Ar, ³⁶Ar, O₂, H₂, CO, He, Ne
# Summary of Past Venus Missions

**Second U.S. Attempt**

**Solar System Exploration Roadmap**
- Discovery, New Frontiers, Flagship

**NRC Solar System Exploration Decadal Survey (New Frontiers 2013)**
1. South Pole-Aitken Basin;
2. Jupiter Polar Orbiter with Probes;
3. Venus In Situ Explorer (2015); and
4. Comet Surface Sample Return

**Longest-lived on Surface** -- 55 min. /127 min.

**Next Proposed Flagship Mission 2020**
- Venus Mobility Explorer – Several Months
  - (Air Mobility vs. Rover)
  - Search for granitic and sedimentary rocks, in-situ analysis of the crust, measurements of oxidation/mineralogic state of iron

---

### Spacecraft Launch Date Type of Mission

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Launch Date</th>
<th>Type of Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venera 1</td>
<td>1961</td>
<td>Impactor; Spacecraft sealed and pressurized with nitrogen</td>
</tr>
<tr>
<td>Mariner 2</td>
<td>1962</td>
<td>Flyby; first to fly by Venus (US)</td>
</tr>
<tr>
<td>Zond 1</td>
<td>1964</td>
<td>Probe and main bus; Entry capsule designed to withstand 80 to 80°C, and 2 to 5 bar</td>
</tr>
<tr>
<td>Venera 2 &amp; 3</td>
<td>1965</td>
<td>Probe and main bus; Entered the atmosphere of Venus; Designed for up to 80 °C / 5 bar</td>
</tr>
<tr>
<td>Venera 4</td>
<td>1967</td>
<td>Stopped transmitting at 25 km; 93 minutes descent; first to descend through the atmosphere; Designed for 300 °C / 20 bar (Russia)</td>
</tr>
<tr>
<td>Mariner 5</td>
<td>1967</td>
<td>Flyby (US)</td>
</tr>
<tr>
<td>Venera 5</td>
<td>1969</td>
<td>Hard-lander; Stopped transmitting at ~20 km (320 °C / 27 bar); 53 minutes descent (Russia)</td>
</tr>
<tr>
<td>Venera 6</td>
<td>1969</td>
<td>Hard-lander; Stopped transmitting at ~20 km (320 °C / 27 bar); 51 minutes descent (Russia)</td>
</tr>
<tr>
<td>Venera 7</td>
<td>1970</td>
<td>First to soft land on surface; Parachute failure, rough landing, landed on the side; 55 min descent / 23 min on surface (Russia)</td>
</tr>
<tr>
<td>Venera 8</td>
<td>1972</td>
<td>Performed as designed; Soft-lander; 55 min descent / 50 min on surface (Russia)</td>
</tr>
<tr>
<td>Mariner 10</td>
<td>1973</td>
<td>Flyby en route to Mercury (US)</td>
</tr>
<tr>
<td>Venera 9</td>
<td>1975</td>
<td>Orbiter (moves out of radio range); soft-lander; first to return photos of surface; 20-55 min descent / 53 min on surface (Russia)</td>
</tr>
<tr>
<td>Venera 10</td>
<td>1975</td>
<td>Orbiter (moves out of radio range); soft-lander; 20+55 min descent / 65 min on surface (Russia)</td>
</tr>
<tr>
<td>Pioneer-Venus 1</td>
<td>1978</td>
<td>Orbiter with radar altimeter; first detailed radar mapping of surface (US)</td>
</tr>
<tr>
<td>Pioneer-Venus 2</td>
<td>1978</td>
<td>Four hard-landers (US)</td>
</tr>
<tr>
<td>Venera 11</td>
<td>1978</td>
<td>Flyby, soft-lander; 80 min descent / 85 min on surface (Russia)</td>
</tr>
<tr>
<td>Venera 12</td>
<td>1978</td>
<td>Flyby, soft-lander; 60 min descent / 110 min on surface (Russia)</td>
</tr>
<tr>
<td>Venera 13</td>
<td>1981</td>
<td>Orbiter, soft-lander; first color images of surface; 55 min descent / 127 min on surface (Russia)</td>
</tr>
<tr>
<td>Venera 14</td>
<td>1981</td>
<td>Orbiter, soft-lander; 55 min descent / 57 min on surface (Russia)</td>
</tr>
<tr>
<td>Venera 15</td>
<td>1983</td>
<td>Orbiter with radar mapper (Russia)</td>
</tr>
<tr>
<td>Venera 16</td>
<td>1983</td>
<td>Orbiter with radar mapper (Russia)</td>
</tr>
<tr>
<td>Vega 1</td>
<td>1984</td>
<td>Flyby, atmospheric balloon probe (Russia / International)</td>
</tr>
<tr>
<td>Vega 2</td>
<td>1984</td>
<td>Flyby, atmospheric balloon probe (Russia / International)</td>
</tr>
<tr>
<td>Magellan</td>
<td>1989</td>
<td>Orbiter with radar mapper (mapped 96% of the surface); first high-resolution global map of Venus (US)</td>
</tr>
<tr>
<td>Venus Express</td>
<td>2005</td>
<td>Orbiter – Ongoing mission (ESA)</td>
</tr>
<tr>
<td>Planet-C</td>
<td>2010</td>
<td>Venus Climate Orbiter – in development (JAXA)</td>
</tr>
</tbody>
</table>
Summary of Enabling Technologies

Telecom
- Satellite Communication
- High temperature motor for antenna gimbal

Mobility Technologies
- Metallic bellows/balloon
- High temperature motor for rover and sample acquisition

Venus Environment Facility
- Launch, transit, entry, descent, land, extended surface operations
- Components & Systems
- GRC & ARC provide all mission phases except near surface

Materials and Joining Technologies
- High temperature, pressure, and corrosion resistant
- Enable higher power conversion efficiencies
- Pressure Vessel Insulation
- Lander mass reduction

Aeroshell Transit and Entry
- Thermal Protection Shell
- Minimize deceleration forces/temperature
- Heat pipe/radiator integration

Thermal Management
- Passive Cooling-1 day
- Active Cooling-1 year
- Hybrid for redundancy and minimal duty cycle
- Aerogel, Multi-layer Insulation

Component Hardening
- Enables warmer coldbay
- High temperature electronics
- Imagers/Optics at interface
- External components/sensors

Power and Storage
- Solar – High Altitude
- Stirling – Low Altitude
- High temperature battery for redundancy and minimal duty cycle
### Summary of Venus Mission Testing Facilities

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Facility/Center</th>
<th>Size (feet)</th>
<th>Pressure (bar)</th>
<th>Temp. (°C)</th>
<th>Simulates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch</td>
<td>SDL/GRC</td>
<td>10x10</td>
<td>1</td>
<td>20</td>
<td>Vibration</td>
</tr>
<tr>
<td>Transit</td>
<td>SPF/GRC</td>
<td>100x122</td>
<td>1.3e-9</td>
<td>-195</td>
<td>Solar Radiation</td>
</tr>
<tr>
<td>Entry</td>
<td>IHF/ARC</td>
<td>Coupon</td>
<td>1</td>
<td>1649</td>
<td>Viscous Heating</td>
</tr>
<tr>
<td>Entry</td>
<td>HTF/GRC</td>
<td>25x20</td>
<td>.143 thru 1</td>
<td>1893</td>
<td>High Velocity</td>
</tr>
<tr>
<td>Entry</td>
<td>20g Centrifuge/ARC</td>
<td>7.6x5.9</td>
<td>1</td>
<td>20</td>
<td>Deceleration</td>
</tr>
<tr>
<td>Descent</td>
<td>Wind Tunnel/ARC</td>
<td>80x120</td>
<td>1</td>
<td>20</td>
<td>Full Vehicle</td>
</tr>
<tr>
<td>Surface</td>
<td>Proposed/GRC</td>
<td>6x10</td>
<td>100</td>
<td>510.2</td>
<td>Pressure &amp; Temp.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Size</th>
<th>Pressure (bar)</th>
<th>Temp. (°C)</th>
<th>Gas Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Georgia Institute of Technology</td>
<td>12&quot;x12&quot;</td>
<td>100</td>
<td>343</td>
<td>Variable</td>
</tr>
<tr>
<td>University of Iowa</td>
<td>5&quot;x12&quot;</td>
<td>90</td>
<td>500</td>
<td>CO₂</td>
</tr>
<tr>
<td>Jet Propulsion Lab</td>
<td>4&quot;x54&quot;</td>
<td>92</td>
<td>500</td>
<td>CO₂, N₂, trace</td>
</tr>
<tr>
<td>Massachusetts Institute of Technology</td>
<td>1&quot;x48&quot;</td>
<td>200</td>
<td>700</td>
<td>CO₂</td>
</tr>
<tr>
<td>Massachusetts Institute of Technology</td>
<td>0.5&quot;x12&quot;</td>
<td>200</td>
<td>700</td>
<td>CO₂</td>
</tr>
</tbody>
</table>

Most larger facilities are available at GRC for each mission phase, except surface. Small Venus facilities at universities NASA needs a large facility, recent study completed indicates feasibility at GRC.
Power and Cooling Options

### Efficiency, %

<table>
<thead>
<tr>
<th>Approach</th>
<th>Efficiency</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free-piston Stirling</td>
<td>17</td>
<td>Alternator cooling required, forms a pneumatic duplex</td>
</tr>
<tr>
<td>Free-displacer Stirling</td>
<td>15</td>
<td>Alternator cooling required, forms a pneumatic duplex</td>
</tr>
<tr>
<td>Thermoacoustic Stirling</td>
<td>13</td>
<td>Alternator cooling required, forms a pneumatic duplex</td>
</tr>
<tr>
<td>Brayton/Rankine</td>
<td>11</td>
<td>High speed rotation gear reduction required for cooling</td>
</tr>
<tr>
<td>Thermoelectric (Segmented)</td>
<td>3-4</td>
<td>Difficult to couple with efficient dynamic cooling</td>
</tr>
<tr>
<td>Solar Array</td>
<td>&lt; 1</td>
<td>Additional development required for high temperature</td>
</tr>
<tr>
<td>Beamed Power</td>
<td>&lt; 1</td>
<td>Energy dissipates in atmosphere, requires development</td>
</tr>
<tr>
<td>Thermionic</td>
<td>&lt; 1</td>
<td>Difficult to couple with efficient dynamic cooling</td>
</tr>
<tr>
<td>Battery</td>
<td>-</td>
<td>Limited mission duration or requires repeated charging</td>
</tr>
</tbody>
</table>

### Efficiency, % of Carnot

<table>
<thead>
<tr>
<th>Approach</th>
<th>Efficiency</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free-piston Stirling</td>
<td>28</td>
<td>Space operations heritage, forms a pneumatic duplex</td>
</tr>
<tr>
<td>Free-displacer Stirling</td>
<td>24</td>
<td>Less bearings required, forms a pneumatic duplex</td>
</tr>
<tr>
<td>Thermo-Acoustic/Pulse Tube</td>
<td>20</td>
<td>Few moving parts, forms a pneumatic duplex</td>
</tr>
<tr>
<td>Brayton/Rankine</td>
<td>18</td>
<td>Gear reduction required from power takeoff</td>
</tr>
<tr>
<td>Thermionic</td>
<td>15</td>
<td>Electrons carry heat across vacuum, requires development</td>
</tr>
<tr>
<td>Thermoelectric (Segmented)</td>
<td>1</td>
<td>Peltier Cooling, Useful for localized cooling</td>
</tr>
<tr>
<td>Mixed Refrigerant</td>
<td>-</td>
<td>High temperature Venus applications not developed yet</td>
</tr>
<tr>
<td>Phase Change</td>
<td>-</td>
<td>Limited mission duration, can complement active cooling</td>
</tr>
</tbody>
</table>

Stirling power and cooling offers most potential when combined into duplex
The Stirling cycle engine, when integrated with a linear alternator, becomes a Stirling cycle power convertor.

With proper masses, spring rates and damping (dynamic/acoustic tuning), the convertor will resonate as a Free-Piston or Thermo-Acoustic Stirling Thermodynamic Cycle Convertor.

- All Wear Mechanisms Have Been Eliminated By Design
- Long Life Operation Is Based On Non-Contacting Operation
What are the Life Limiting Mechanisms?

Potential life limiting mechanisms:
- Wear
- Fatigue
- Creep
- Permeation
- Radiation

Motion does not limit the life:

Kinematic
- Sliding seals
- Rolling element bearings

Free Piston
- No sliding seals
- No rolling element bearings

Free-Piston Thermo-Acoustic
- High amplitude acoustical wave circuit replaces displacer
- One less moving part
- Less efficient, but simpler

Wear mechanisms have been eliminated
- Based on non-contacting operation
**Stirling Duplex Principle of Operation**

GPHS Heat, 1200 °C

Power and Cooling Directly Pneumatically Coupled

Power

Venus 500 °C

Cooler

Power converter heat reactor sink fins

Electronics vessel cold finger (electronics and sensors containment vessel not shown)

GPHS module, 250w each
- Heat acceptor bridge
- Regenerator

Piston
- Compression space
- Power converter piston housing

Alternator housing

Chain drive

Mechanical

Linear alternator losses, 94% efficient

- Mechanisms impact reliability
- Lubrication required

Chiller, Heat from Capsule, 30 °C

Mechanical

Power

Venus

Electrical

Pneumatic

Most efficient method of connecting power with active cooling

Linear alternator losses, 94% efficient

Mechanical

Chiller, Heat from Capsule, 30 °C

Electrical

Pneumatic

Most efficient method of connecting power with active cooling

Venus

500 °C

Power

Venus

500 °C

Chiller, Heat from Capsule, 30 °C

Mechanical

Linear alternator losses, 94% efficient

- Mechanisms impact reliability
- Lubrication required
Single-Stage Cooling System

- Heat Loss Through Insulation
- Heat Rejection From Stirling
- Heat Rejection From Cooler
- Power to Instruments & Alternator Losses
- Heat Lifted
- Heat Leak From Environment

Energy Path is Shown
VISM Lander Configuration, 1993

**Radioisotope Fuel, 1407 °C**
- 2000 W(t), 1301 °C
- Isotope Heat Source
- 50 W(t), 1301 °C
- Insulation Heat Loss
  - 50 W(t), 1301 °C
  - Thermodynamic Losses
    - 500 °C

**Stirling Engine, ~31% eff.**
- 1950 W(t), 1177 °C
- Mechanical Losses, Displacer Drive
- 608 W(m)
- Mechanical Losses, Kinematic Drive
- 40 W(m)
- Rotary Alternator
- 25 W(m)
- Refrigerated Payload Bay
- 5 W(t), 25 °C
- Electronic Payload
  - 2 W(e), avg.
  - 2134 W(t), 500 °C
- Battery (Na/S), 600 °C
- 18 W(t), 25 °C
- 150 W(e), 1000s/d
- 25 W(t), 25 °C

**Stirling Cooler**
- COP = .37
- 543 W(m)
- 109 W(t), 25 °C
- 134 W(t), 500 °C
- 742 W(t), 500 °C
- 45 W(t), 25 °C
- 199 W(t), 25 °C

**Payload Bay Structure and Penetrations**
- 109 W(t), 25 °C
- 25 W(t), 25 °C
- 25 W(t), 500 °C

**Payload Bay Canister (Ti, 15" dia., 0.025" wall, 25 °C)**
- 1.3
- Multifoil Thermal Insulation (Ni)
- 1.8
- Multifoil Thermal Insulation (Mo, 0.0003", 60 layer)
- 1.5

**Stirling Engine (Mo)**
- 10.0

**Stirling Cooler & Alternator**
- 9.1

**Heat Pipes and Radiators**
- 7.0

**Heat Source Pressure Shelf (Ti, 0.25" wall, five 0.20" stiffeners)**
- 9.6

**Heat Source Canister (Ir)**
- 4.0

**Radioisotope Heat Source (8 GPHS)**
- 11.6

**TOTAL Mass (kg)**
- 65.8

**Venus Environment**
- 500 °C

**Electronic Payload 25 °C**
- 2134 W(t), 500 °C
Thermodynamic Two Stage System

1st Stage Cooler
- Lifts 400W from 30°C to 250°C
- Rejects 1358W

GPHS Modules
- 15449W@1200°C

2nd Stage Cooler
- Lifts 2068W from 250°C to 500°C
- Rejects 5363W

Heat leak-in from Venus surface
- 700W at 460°C

Insulated Inner Vessel
- Refrigerated to 30°C
- Electrical 400W

Outer Pressure Vessel
- Electrical 400W

Venus 500°C
- Heat enters 700W

By staging the cooling, the power requirements drop considerably.

Shown here are two stages, one additional stage would be optimal.
Single-Stage Duplex Performance
- Assuming max. 30% of Carnot refrigerator, though numerous studies suggest 55-60% of Carnot possible.
- Duplex reaches 5% efficient at max. temp
- But reaches 20% with warmer coldbay
- High temperature electronics development important!

Multistage vs. Single Stage Cooling
Function of electrical power requirements
- 700 W heat leak in
  - 1200°C Hot-end
  - 250°C Buffer
  - 30°C Coldbay
- 55% of Carnot Convertor
  - Case 1 = 20% of Carnot cooler
  - Case 2 = 30% of Carnot cooler
GPHS Design Limits

- Fabric Weave Pierced Fabric Graphite Impact Shells vendor unavailable
- Carbon bonded Carbon Fiber Thermal Insulation Sleeve
- Iridium cladding temperature limit determines GPHS aeroshell max. temperature
- $1266^\circ$C maximum possible

DOE seeks authorization for new US Pu$^{238}$ production (FY10)

- First output in 2015, full production by 2017 (1/2 capacity to NASA), 5kg/yr, $\sim 5.6 = 8$ GPHS/year

<table>
<thead>
<tr>
<th>GPHS Cover Gas</th>
<th>Max. Aeroshell Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>1026</td>
</tr>
<tr>
<td>Helium</td>
<td>1266</td>
</tr>
<tr>
<td>Air</td>
<td>1189</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1199</td>
</tr>
<tr>
<td>Argon</td>
<td>1119</td>
</tr>
<tr>
<td>Xenon</td>
<td>1099</td>
</tr>
</tbody>
</table>

Plutonium Supply vs. Demand w/Flagship
High Temperature Materials

Nickel base superalloy

- Current Stirling hot-end material (MarM-247) is being developed in the ASC/ASRG project to operate for 17 years at 850 °C.
- For Venus missions of less than 1 year, MarM-247 needs to be evaluated for potential use at temperatures up to 1000 °C.
- The use-temperature may be able to be raised to as high as 1100 °C.

Refractory

- For higher temperatures, a different class of material would be required.
- GRC conducted initial development of advanced materials (refractory metal alloys and ceramics) specifically for high-temperature Stirling applications.

Although not fully mature at the present time, these advanced materials have the capability of operating at temperatures as high as 1200 °C.

Higher hot-end temperatures increases efficiency

Ref. R. Bowman
High Temperature Alternator Development

- **Option 1: Permanent Magnet Type**
  - Venus ambient temperature $\approx 460 \, ^\circ C$
  - Known SmCo type magnets may be used potentially up to $300 \, ^\circ C$
  - Magnet Remanence declines with increasing temperatures

- **Option 2: Electromagnet Type**
  - Based on induction generator technology
  - Battery or some other external power source needed during start-up
  - Coil provides magnetic field, not used yet in Stirling industry.

GRC has an existing laboratory for the evaluation and development of high-temperature linear alternators. Wire insulation is primary limiting component, but ceramics could be considered. Fortunately, duplex design can refrigerate itself!
Organics Maximum Operating Temperature

<table>
<thead>
<tr>
<th>Organic Compounds</th>
<th>Use/Function</th>
<th>Temp. °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viton (FKM)</td>
<td>Gasket Seal</td>
<td>200</td>
</tr>
<tr>
<td>Silicon</td>
<td>O-ring</td>
<td>300</td>
</tr>
<tr>
<td>Hysol EA9394</td>
<td>Adhesive Potting</td>
<td>177</td>
</tr>
<tr>
<td>Loctite 2422</td>
<td>Thread Locker</td>
<td>343</td>
</tr>
<tr>
<td>Nomex Paper</td>
<td>Coil Backing</td>
<td>220</td>
</tr>
<tr>
<td>Polyamide</td>
<td>Coil Insulation</td>
<td>240</td>
</tr>
<tr>
<td>Polythermalize</td>
<td>FLDT Coil Insulation</td>
<td>200</td>
</tr>
<tr>
<td>Teflon</td>
<td>Wire lead insulation</td>
<td>260</td>
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<tr>
<td>Tra-bond</td>
<td>FLDT Coil Potting</td>
<td>190</td>
</tr>
<tr>
<td>Xylan</td>
<td>Bearing Lubricant</td>
<td>260</td>
</tr>
<tr>
<td>Matrimid 5218</td>
<td>Adhesive</td>
<td>250</td>
</tr>
</tbody>
</table>

- **ASC** is being developed for 17 years of ASRG operation and ~130 °C maximum alternator temperature.
- Fission Surface Power convertor is being developed for ~150 °C alternator temperature with similar materials as ASC.
- CTPC was developed, as part of the SP-100 program, for ~273 °C alternator temperature for a 60,000-hour life:
  - Short-term tests completed at temperature
  - Still needed long-life, ceramic-coated coil development
- Tradeoffs of maximum operating temperature vs. required development and risk need to be investigated in terms of:
  - Long-term thermal stability
  - Outgassing
  - Synergistic effects, e.g., radiation + temperature + aging time
  - Selection and validation of high temperature alternatives, especially for ~177 °C or higher alternator

Note that higher temperatures permitted for shorter missions, Maximum use temperatures assume unlimited duration.

Ref. E. Shin
Variable Conductance Heat Pipe

- Allows option of commanded stop and restart of Stirling for GPHS installation and taking sensitive science data with zero vibration and minimal EMI
- Ability to protect Stirling heater head in event of unexpected Stirling shutdown and allow restart if possible
- Reduces temperature differences in hot-end components
- Minimal mass or performance impacts, 1000 °C operation

VCHP off during normal operation (NCG covers condenser) – when convertor stops, temperature and alkali-metal vapor pressure increase to uncover condenser and remove GPHS heat
  - Designed to turn on with ~30 °C temperature rise to not risk normal operation and minimize effect on convertor life when convertor off

When coupled with currently available energy storage technology, enables quiet seismometer and magnetic field measurements.

CTPC Operated at:
- 777 °C hot-end,
- 252 °C cold-end,
- 3-4 hours at max. temp.
- 1500 hours total testing (527/127 °C)

70Hz, 15.0 MPa, 12 kWe, Nov. 1992

ASC-1 and ASC-1HS
Single Convertor Operating over 300 hours
Total hours on all convertors: 1257
- 850 °C hot-end
- 90 °C cold-end
- 38% efficient, 1.3 kg, 102 Hz,
- ~3.6MPa,
- 88 W up to 114 W, 2005
• Sunpower design is coaxial with heat exchangers surrounding the Thermal Buffer Tube
• Northrop-Grumman design is circular with thermal buffer tube open to environment
• Sunpower convertor performance is presently equal to Northrop Grumman

Sunpower Northrop Grumman
Pressure 3.65 MPa (530 psia) 5.28 MPa (765 psia)
Frequency 100 Hz. 125 Hz.

Ref. G. Wood & M. Tward
Hybrid cooling provides:
- redundancy,
- potential mass savings,
- lower duty cycle,
- longer-lived than passive

Hybrid power provides:
- redundancy,
- potential mass savings,
- higher peak power,
- longer-lived than passive
**Mission Capability Summary**

### Flagship Class Mission Concept

**Venus Geophysical Network**

- **Scientific Objectives**
  - Determine the internal structure and seismic activity of the planet
  - Monitor the circulation of the atmosphere

- **Exploration Metrics**
  - At least three stations on the surface of Venus
  - Operate for at least one Earth year

- **Science Payload**
  - Camera, descent imager
  - Seismometer network
  - Meteorology station with pressure, temperature, and wind velocity sensors

- **Technology & Heritage**
  - Extreme environments technologies (pressure vessel, thermal management, corrosion)
  - High-temperature electronics
  - Radioisotope power system w/ active cooling
  - Long-duration operations in situ
  - Passive isolation and survival technology from VISE

**Mission & LV Class**

- Flagship Class Mission
- Launch Vehicle: TBD

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### Flagship Class Mission Concept

**Venus Mobile Explorer**

- **Scientific Objectives**
  - Composition and isotopic measurements of surface and atmosphere
  - Near IR descent images
  - Acquire and characterize core samples at multiple sites
  - Demonstrate key technologies for VSSR

- **Exploration Metrics**
  - Operate in Venus surface environment for 90 days
  - Range and altitude if aerial vehicle TBD
  - Range across surface if rover TBD

- **Science Payload**
  - Neutral-mass spectrometer with enrichment cell
  - Instruments to measure elements and mineralogy of surface materials
  - Imaging microscope

- **Technology & Heritage**
  - Extreme environments technologies (pressure vessel, thermal management, corrosion)
  - High-temperature electronics
  - Sample acquisition and handling in Venus near-surface environment
  - Air mobility system (e.g., inflatable bellowes)
  - Radioisotope power system w/ active cooling
  - Long-duration operations in situ

**Mission & LV Class**

- Flagship Class Mission
- Launch Vehicle: Delta IV
- Atlas V

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### Flagship Class Mission Concept

**Venus Surface Sample Return**

- **Scientific Objectives**
  - Measure isotopic composition of oxygen in surface rocks
  - Measure isotopic composition of trace elements to characterize core and mantle formation
  - Determine the age of returned rocks

- **Exploration Metrics**
  - Return samples of Venus rock soil and atmosphere for analysis on Earth
  - Mission duration: TBD
  - Time on surface: TBD (short lived)

- **Science Payload**
  - Camera and Descent imager
  - Sample identification as needed
  - Sample-acquisition system
  - In-situ instrumentation

- **Technology & Heritage**
  - Extreme environments technologies (pressure vessel, thermal management, corrosion)
  - High-temperature electronics
  - Sample acquisition and handling in Venus near-surface environment
  - Multi-stage ascent air-mobility system to lift sample to launch altitude
  - Rendezvous and sample-return systems inherited from Mars Sample Return
  - Heritage from prior Venus missions: e.g., VISE, Venus Geophysical Network, VME

**Mission & LV Class**

- Flagship Class Mission
- Launch Vehicle: TBD

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**VEXAG flagship class missions specifically suggest the use of a radioisotope power system with active cooling for **three out of the four concepts**, including Venus Surface Sample Return.**

**Ref. VEXAG report**

- Numerous studies over the past 15 years have indicated the need for duplex Stirling power/cooling on Venus.
- GRC and Industry partnered to develop flight convertors for the radioisotope generator and are primed to begin development for the Venus application.
Remaining Technical Challenges

To combine a Stirling heat engine and refrigerator into a long-lived duplex machine with at least two cooling stages.

To achieve a high thermodynamic efficiency that will keep the GPHS module requirements manageable.

To create a complete system design with the multi-stage refrigerator integrated into the Venus platform.

To mitigate potential electromagnetic or mechanical vibration effects.
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Official Bulletins: Bulletins are distributed under the A35 distribution list resource. Unique information generated from the A35 database is printed on each bulletin including the custodian's name (recorded as an e-mail address), their mail stop, the board location, and the assigned bulletin board number.


A35-GRC Official Bulletin Board List: The A35 listing is a GRC database that includes all information unique to the official bulletin board posting network. The mailroom staff controls and updates the A35 database. The mailroom is located in building 21 annex, room 8, and can be reached by phone at 216-433-2247/2251. The A35 listing is a shared resource used by the GRC print shop for distribution purposes only.

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1. Bulletin board number
2. Former custodian’s name
3. New custodian’s name
4. New custodian’s phone number
5. New custodian’s mail stop
6. New custodian’s room number

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Form NASA-570a: Display time is continuous.

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