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VENUS SURFACE POWER AND COOLING SYSTEMS

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ABSTRACT

A mission to the surface of Venus is would have high scientific value, but most electronic devices and sensors cannot operate at the 450 °C ambient surface temperature of Venus. Power and cooling systems were analyzed for Venus surface operation. A radioisotope power and cooling system was designed to provide electrical power for a probe operating on the surface of Venus. For a mission duration of substantial length, the use of thermal mass to maintain an operable temperature range is likely impractical, and active refrigeration may be required to keep components at a temperature below ambient. Due to the high thermal convection of the high-density atmosphere, the heat rejection temperature was assumed to be at a 500 °C radiator temperature, 50 °C above ambient. The radioisotope Stirling power converter designed produces a thermodynamic power output capacity of 478.1 watts, with a cooling power of 100 watts. The overall efficiency is calculated to be 23.36 %. The mass of the power converter is estimated at approximately 21.6 kg.

NOMENCLATURE

Q_h	GPHS heat input (W)
Q_r	Heat rejected (W)
T_c	radiator temperature (C)
T_h	hot-side temperature (C)

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1. INTRODUCTION

1.1 Background

The surface of Venus is a target of great interest to science. The National Academies of Science Space Studies Board decadal study, *New Frontiers in the Solar System: An Integrated Exploration Strategy*¹, ranked a Venus surface In-Situ Explorer as one of the five highest priorities for Medium-class future missions. Crisp *et al.*² called the environment of Venus "among the most enigmatic in the solar system." Understanding the atmosphere, climate, geology, and history of Venus could shed considerable light on our understanding of our own home planet. Yet the surface of Venus is the most hostile operating environment of any of the solid-surface planets in the solar system.

The surface of Venus has been explored by a number of missions from Earth, including the Russian Venera missions, which landed several probes on the surface³, and the American Pioneer missions, which flew both orbiters and atmospheric probes to Venus³. The longest-lived of the Russian Venera landers lasted less than two hours on the surface of Venus. One American Pioneer probe made it to the surface and survived about an hour.

The greatest difficulty is the surface temperature of Venus, 452 C (850 F)³⁻⁷. The surface temperature does not change significantly between daytime and nighttime. The tops of Venus' mountains are slightly cooler: at the top of Maxwell Montes (10.4 km above mean elevation), pressure is 48 bars and temperature is only 390 C (725 F).

The atmospheric pressure at the surface is 92 bars, equivalent to the pressure a kilometer under the ocean, and the atmosphere is primarily of carbon dioxide. While the Venus clouds are concentrated sulfuric acid droplets, this is not important to the surface operation, since the surface conditions are too hot for liquids to exist. However, the atmosphere at the surface will contain significant amounts of anhydrous sulfur compounds, such as SO₃, which are corrosive.

The cloud layer of Venus is thick. The surface does not ever get a direct view of the sun, and the solar intensity at the surface is about 2% of the intensity above the atmosphere. The light level is equivalent to the light level during a rainy day on Earth.

1.2 Mission Summary

The objective was to develop a concept and technology for science-driven, technology-enabled exploration of Venus surface and atmosphere⁷. The mission includes both surface robots, designed with an operational lifetime of 50 days on the surface of Venus, and also solar-powered airplanes to probe the middle atmosphere. The airplane design is discussed elsewhere⁸⁻¹¹.

Figure 1 is a conceptual design of the surface rover⁷, with a small isotope power system shown on the rear side providing power.

The mission requirements were designed to allow a surface exploration mission comparable in scope to the Mars rover missions:

- baseline mission duration: 50 days
- mission to operate at multiple latitudes across the planet
- mission to operate at the average surface altitude
- seismometers emplaced at a minimum of four surface locations
- No night operations required.

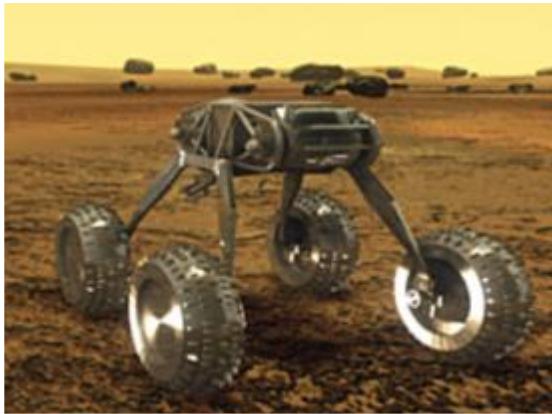


Figure 1: Visualization of rover on Venus

The design study evaluated a solar-powered airplane for atmospheric exploration, and a nuclear-isotope powered rover for the surface mission. The design trade-off selected for the detailed mission design uses a surface rover along with an associated airplane for the rover control electronics. A dedicated airplane is associated with each surface rover. The airplane carries the rover's computer, and the electronics package on the rover itself is a simple package with discrete components, made using only high-temperature semiconductors.

2. POWER SYSTEM SELECTION

2.1 Surface Power system

Power systems considered for the rover power included microwave beamed power, solar power, and radioisotope power systems. The radioisotope system was selected based on the technology availability. Both thermoelectric and dynamic (Stirling conversion) options were analyzed. In addition to the power system, a Stirling refrigeration system was designed.

An overview of power system trade-offs is listed in Table 1.

While advances are currently being made in the field of high-temperature solar cells, and 450 C operating temperatures are not beyond the range of technology in development^{12,13}, the highest operating temperature solar cells are responsive only to the blue portion of the solar spectrum. The Venus surface illumination is deficient in shortest wavelength portion of the spectrum, due to Rayleigh scattering in the thick atmosphere^{4,5}. Because of this, and to the generally low light levels available on the surface, we eliminated solar power systems early in the study. However, due to the rapid development of high operating temperature photovoltaics, this decision should be re-evaluated in the future.

Powering the Venus surface rover is a potential application for microwave power beaming. An orbital station converting solar energy to microwaves is not practical for Venus, since the slow rotation means that synchronous orbit is too far from the planet. A solar power station would be placed in the atmosphere above the cloud level, 60-70 km from the ground level, where it would receive essentially full sunlight.

Radioisotope power source

- Although 460 C is a higher heat rejection temperature than most dynamic conversion approaches, should be possible
- Dynamic or thermoelectric conversion approaches possible
- Baseline technology chosen for the Venus rover

Microwave beamed power

- Station in atmosphere produces solar power; Power beamed to surface by microwaves
- Many technical questions need to be answered
- Possible backup approach-- not analyzed in detail

Solar power

- Low light levels at surface
- high temperature at surface makes solar power impractical
- Approach requires new technologies to be developed

Chemical (Battery or Fuel Cell) Storage

- Requires high temperature technology
- Practical approach for short missions or low powers

Table 1: Power system trade-offs

Lighter-than-air vehicles and airplanes were examined as platforms for the beaming station; airplanes were selected due to the difficulty of keeping an airship stationary over one location. The station would transform the power into a microwave beam, which would be sent the short distance to the surface.

Microwave power beaming was rejected due to the low technology readiness, and the lack of data on the operation performance and lifetime of receiving rectennas at the Venus ambient surface temperature. The beamed power option had several advantages, and should be re-evaluated as new technology becomes available.

2.2 Thermoelectric Power Converter

Thermoelectric conversion technologies have the highest technological readiness level of any nuclear isotope power system. This is the power approach used on many planetary missions, including Viking, Voyager, Galileo, and Cassini. Compared to dynamic conversion systems, thermoelectric systems have relatively low efficiency, however, the absence of moving parts makes them highly reliable. The power is directly produced as electricity; if mechanical power is required, a generator is needed.

Parameter	Value
Type	thermoelectric
Power produced	30 Watts
T _h	1077 C
T _c	600 C
Conv. efficiency	5%
Input power Q _h	594 W
Heat Rejected, Q _r	564 W

Table 2: performance of radioisotope thermoelectric converter (RTG).

A Pu-isotope General Purpose Heat Source (GPHS) was baselined for the thermal power source to provide heat to the power converter.

For the analysis case, we assumed thermoelectric converters similar to those used on Cassini. While the high temperature of waste-heat rejection to the Venus atmosphere reduces the theoretical Carnot efficiency of any thermal converter, the density of the atmosphere means that heat transfer is very efficient, and hence the required area of the convective radiators is small.

The assumed hot-side temperature (T_h) is 1350 K, and the cold-side temperature (T_c) ejected to the radiator is 870 K. The calculated net thermal to electrical efficiency was 0.05 (5%). A GPHS heat input Q_h of 594 W was required to produce 30 W of output electrical power. The total heat rejected is 564 W.

Three such units are required for 100 watts of electrical power. No mechanical power for cooling systems is produced.

2.3 Stirling Power Converter Performance

For the Stirling case, Plutonium-isotope General Purpose Heat Sources were baselined for the thermal power source to provide heat to the power converter. Each GPHS module provides 250 watts of thermal energy.

The design used a "beta" configuration, where the displacer piston and the power piston are collinear, with He at 6 MPa as the working fluid, and a hot-sink wall temperature T_h of 1200 °C. The waste-heat radiator consisted of twenty-four 32.5 cm² vertical fins spaced around the circumference of the cold-side cylinder, for a total radiator area of 0.078 m². Using this radiator configuration, the predicted cold-side temperature is 500 °C, very close to the Venus ambient

The Sage™ model predicted a mechanical power output of 478 watts, which slightly exceeded the required 469 watts. The required heat input Q_h was 1740 watts. This gave a thermodynamic efficiency of 27.5 %, slightly more than half of the theoretical Carnot efficiency neglecting thermal losses of 47.5 %. Further details are in references 14-15.

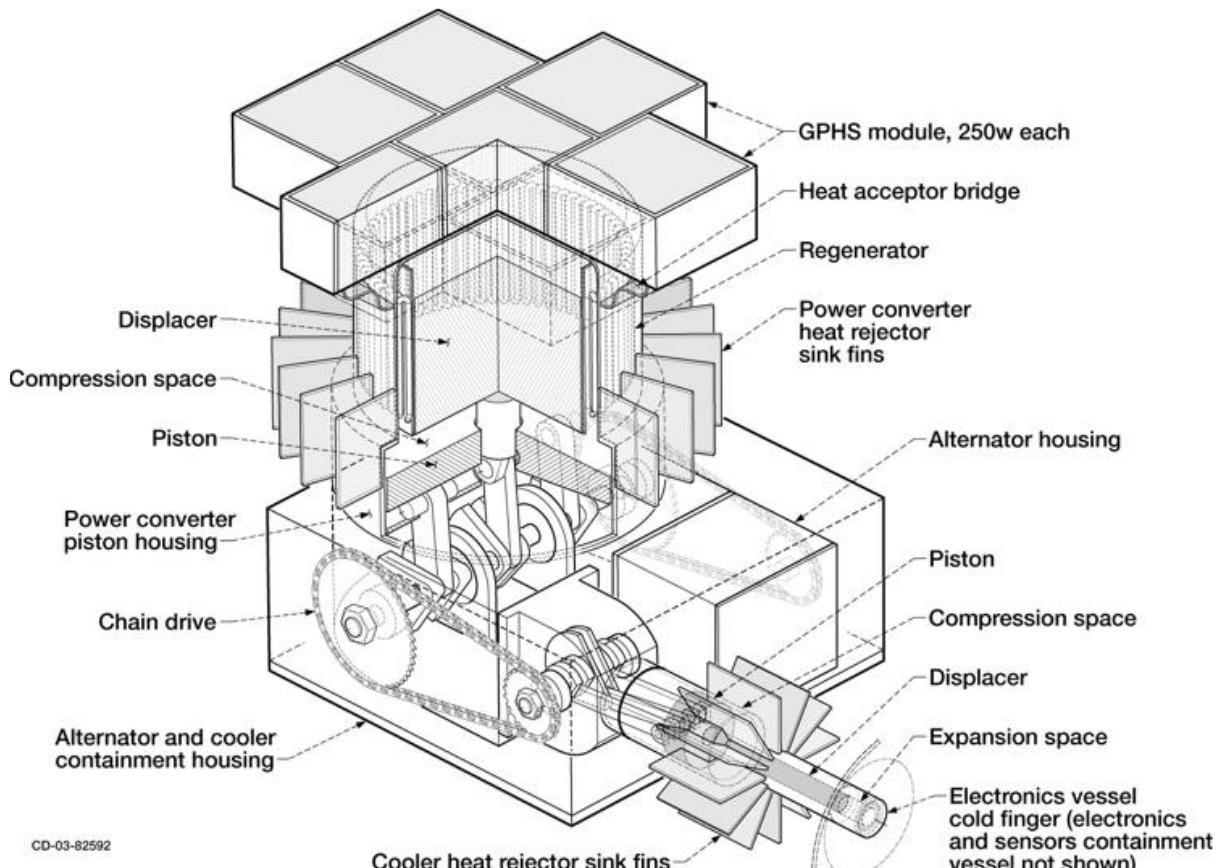
It was assumed that the mechanical efficiency of the power converter design would be on the order of 85 % based on results of experimental measurements taken from kinematic Stirling engines laboratory-tested at NASA Glenn during the 1980s. The overall efficiency is calculated to be 23.4 %. The mass of the power converter alone is roughly estimated at approximately 21.6 kg at this conceptual stage of design. Reference 14 gives more details of the design.

The mechanical power is produced at a shaft speed of 600 rpm. While it might be possible to design a rover to use the mechanical power directly for propulsion, in this case we assumed that the drive power was converted to electrical power and used to power electrical drive motors.

From the total available 400 watts, 100 watts of electrical power are generated, and 280 watts of mechanical power is available to be used for active cooling of the electronics enclosure¹⁵⁻¹⁶. Seven GPHS modules are required to produce the mechanical and electrical power.

Figure 2 shows the overall configuration, including both the generator and the Stirling cooler.

Parameter	Value
Type	Stirling cycle
Power output	478W
Source	7 250-W GPHS units
T_h	1200 C
T_c	500C
Heat input	1740 W
Heat rejected	1267 W
Overall efficiency	23.4%
Mass	21.6 kg

Table 3: performance of radioisotope Stirling converter**Figure 2: Power converter and cooler**

2.4 Electrical Power Conversion

To produce electrical power from the mechanical power of the driveshaft of the Stirling engine requires either an electrical motor-generator.

A high-temperature electric motor/ generator, developed at NASA Glenn for jet engine applications, is used in generator mode to convert the mechanical power into electrical power. This prototype had been tested through multiple thermal cycles between room temperature and

540 °C, and has completed testing at 540 °C for an accumulated operating time of over 27.5 hours¹⁸. The motor uses magnetic suspension to avoid the need for high-temperature lubrication.

For the other moving parts of the generator, a number of lubrication technologies have been developed for high-temperature applications. For this application, high-temperature silicon nitride (Si_3N_4) bearings using cesium silicide lubricant were assumed. were chosen. This technology, developed by the Air Force Research Laboratories, has been tested to 1250 F (675 C) for 50 hours.

3. CHEMICAL ENERGY STORAGE

3.1 Sodium sulfur battery

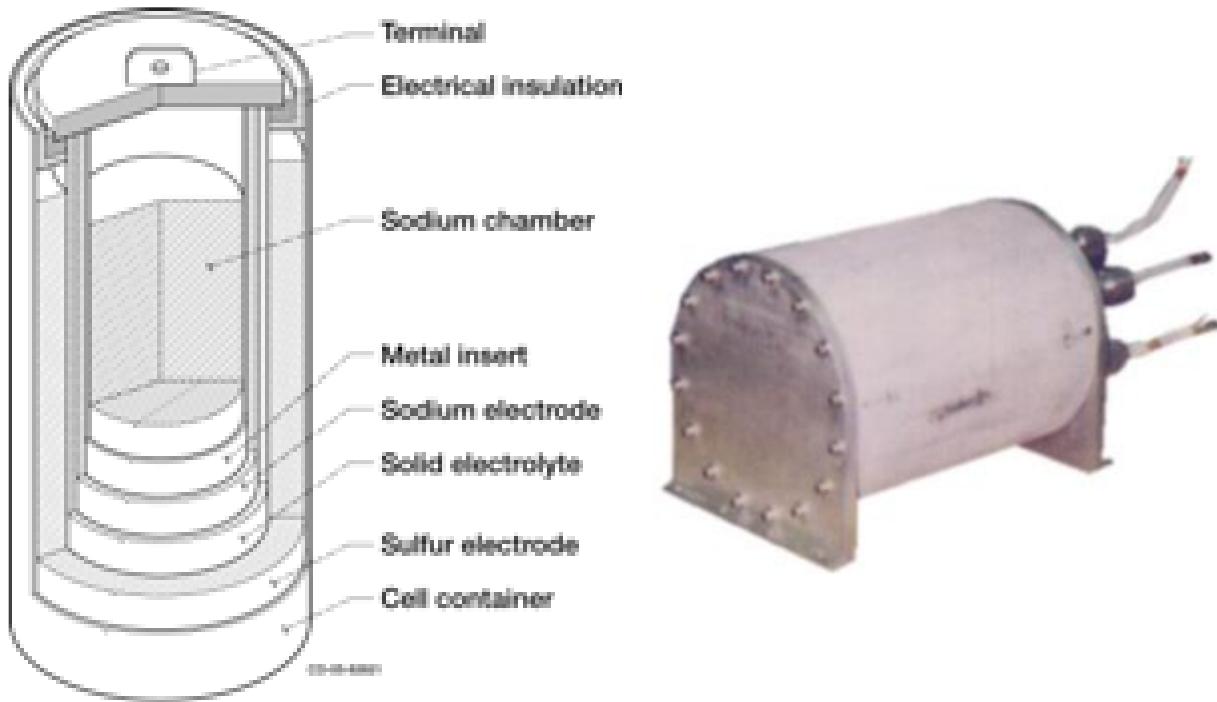
Fuel cells and sodium sulfur batteries were analyzed as methods of chemical energy storage. For short-duration or low power missions, chemical energy storage can be used as primary power. For longer duration, chemical storage technologies can be charged at a low rate and discharged at a higher rate, allowing a low-power primary energy conversion system to provide high peak power for momentary loads.

The sodium-sulfur battery was chosen as a battery which operates efficiently at high temperature, and thus may be usable on Venus. It is a rechargeable, and hence may be used as primary power (assuming it is charged before landing), or as a battery to buffer a low-average power system to provide adequate power for "burst" loads, such as drive power or a high-power radio transmitter.

Sodium-sulfur batteries are well demonstrated on Earth¹⁸. Figure 3 shows a schematic of a typical battery, using liquid sodium and sulfur as reactants and a solid electrolyte separator based on zirconium oxide ceramic. They have very high efficiency, with higher power density and lower self-discharge than lithium cells. The primary difficulty with sodium-sulfur batteries for terrestrial application is the high operating temperature (typically 350C) required to keep the sulfur liquid; this disadvantage is turned to an advantage for Venus surface operation.

A prototype NaS battery has been operated successfully in orbit on a space-shuttle flight (figure 4).

Typical operating temperature for terrestrial applications is 290-390C (set by the vapor pressure of sulfur). At Venus pressure of 92 bar, the sulfur remains in liquid form even at Venus surface temperatures of 460C. Operation at 460C has been demonstrated at 92 bar pressure¹⁸.

**Figure 3:** Schematic of sodium-sulfur battery**Figure 4:** Photo of sodium-sulfur battery flown on Space Shuttle.

3.2 Chemical Energy Storage

An alternative to a battery for chemical energy storage is to use a solid-electrolyte fuel cell.

Either hydrogen or carbon monoxide (CO) could be used as the primary chemical energy source. Either of these would be reacted with oxygen to produce energy. Hydrogen has a difficulty of being difficult or impossible to store at Venus surface temperature. The fuel cell chosen was a CO/O₂ fuel cell¹⁹, using a doped zirconia solid electrolyte²⁰. This was chosen over hydrogen because of the difficulty of hydrogen storage at high temperatures. Carbon dioxide, on the other hand, is the main component of the Venus atmosphere. This allows the possibility of using ambient CO₂ as the source material.

The CO-O₂ fuel cell technology has been demonstrated on Earth. The fuel cell can be made rechargeable by addition of an electrolyzer. The principle has been demonstrated on Earth. The fuel cell uses a yttria-stabilized zirconia as a separator and electrolyte. The zirconia-based solid electrolyte is being developed commercially for terrestrial applications in hydrogen fuel cells. The solid electrolyte requires a 600-1000C nominal operating temperature, slightly higher than Venus ambient. Specific power density of up to 100 W/kg has been demonstrated with hydrogen fuel cells; the same technology can be used with carbon monoxide reactants.

4. STIRLING COOLER

4.1 Stirling Cooler overview

The power level of this system was selected to allow the electronics enclosure to be cooled to 300C, the maximum operating temperature of a high-temperature microcontroller to operate. The 400W power system was sized to provide sufficient power to allow the refrigeration system to be

run. (An alternate rover design was also analyzed⁷, which used ambient-temperature electronics in order to avoid the need for a refrigeration system.)

The main heat load on the cooler is from the high temperature ambient surface environment on Venus. The electronics package was mounted in a thermal enclosure. This incorporated 5 cm thickness of ceramic blanket insulation on a 10-cm spherical electronics enclosure, the ambient heat load was estimated at approximately 77 watts. With an estimated quantity of 10 watts of heat generation from electronics and sensors, and to accommodate some level of uncertainty, the total heat load requirement was rounded up to an even 100 watts.

The design for cooler system as selected to keep electronics at operating temperature under 300C, to allow a high-temperature silicon-on-insulator (SOI) microcontroller to be used.

Several different cooling cycles, including both single- and two-stage systems, were investigated. A single stage, vapor compression cooling cycle proved to be unacceptable because of the very large compression ratio required. The candidate cooling system analyzed was a one-stage Stirling cooler with a pressure ratio of approximately 10^{14} .

4.2 Cooler Performance

A candidate Stirling cooler was designed and the performance analyzed using the Sage™ model. The cooler was able to lift 105.7 watts of heat from a cold sink temperature of 200 °C, and rejected 344.6 watts of heat at a hot sink temperature of 500 °C. The required power input was 238.9 watts. This gave an estimated thermodynamic Coefficient of Performance of 0.442 (The maximum theoretical Coefficient of Performance is 1.58.)

Parameter	Value
Type	Stirling cycle
Stages	1
Heat sink temperature	500 C
Cold temperature	200C
Heat transferred	105.7 W
Heat rejected	344.6 W
Overall coefficient of performance	37.6%
Mass	1.6 kg

Table 4: Stirling Cooler parameters

The Sage™ model incorporated fluid friction effects in the thermodynamic performance predictions but did not incorporate mechanical bearing or moving contact friction. To account for these mechanical losses, a mechanical efficiency of 85% was assumed. This gave an overall COP of approximately 0.376.

The mass of the cooler was roughly estimated at approximately 1.6 kg at this conceptual design stage. References 15-16 summarize technical details of the cooler.

5. PRESSURANT

If the electronics are at Venus pressure, the interior needs to be sealed from atmosphere. The mass required for a pressure vessel to withstand 92 bar surface pressure of Venus is impractical,

and hence it is desirable that interior of the electronics enclosure should be pressurized to prevent it from being crushed.

The pressurizing gas needs to have low thermal conductivity. Several approaches to pressurization were investigated. A cylinder of compressed gas could be brought to Venus and the enclosure pressurized on descent. Another approach is to use a material that can be transported as a liquid, and then vaporizes at the equilibrium temperature of the electronics enclosure.

Several pressurant gasses were investigated. The pressurant selected was the hydrofluorocarbon HFC 236fa. This has the properties of extremely low thermal conductivity, storable in liquid form for transport, gaseous at the operating temperature, and highly inert. Most notably, it does not decompose to outgas HF at high temperature).

6. CONCLUSIONS

A design study for a mission to investigate the surface and atmosphere of Venus⁷ was completed. In order to operate the rover at the high operating temperature at the surface of Venus, new power systems are needed. A conceptual design for a power system was undertaken, with performance at Venus surface temperature and pressure that will allow operation of a science rover.

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