Available online at www.sciencedirect.com
ScienceDirect
PERGAMON
Acta Astronautica 61 (2007) 995–1001
ACTA ASTRONAUTICA
www.elsevier.com/locate/actaastro

Venus surface power and cooling systems☆

Geoffrey A. Landis*, Kenneth C. Mellott[1]

NASA John Glenn Research Center, 21000 Brookpark Road, Cleveland, OH 44135, USA

Received 14 June 2005; accepted 11 December 2006
Available online 1 May 2007

Abstract

A mission to the surface of Venus 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 W, with a cooling power of 100 W. The overall efficiency is calculated to be 23.36%. The mass of the power converter is estimated at approximately 21.6 kg.
Published by Elsevier Ltd.

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 ranked a Venus surface In Situ Explorer as one of the five highest priorities for medium-class future missions [1]. 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 surface [3], and the American Pioneer missions, which flew both orbiters and atmospheric probes to Venus [3]. The longest-lived of the Russian Venera landers lasted less than 2 h on the surface of Venus. One American Pioneer probe made it to the surface and survived about an hour.

The greatest difficulty is the high surface temperature of Venus, 452 °C (850 F) [3–7]. The surface temperature does not change significantly between daytime and nighttime.

The atmospheric pressure at the surface is 92 bar, equivalent to the pressure a kilometer under the ocean, and the atmosphere is primarily composed of carbon

☆ A slightly earlier version of this paper was presented as paper IAC-04-R.2.06, 55th International Astronautical Federation Congress, Vancouver BC, Canada, October 4–8 2004.

* Corresponding author. Tel.: +1 216 433 2238; fax: +1 216 433 6106.
E-mail address: geoffrey.a.landis@nasa.gov (G.A. Landis).
[1] Current affiliation: PH-I1, NASA Kennedy Space Center, FL, 32899.

0094-5765/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.actaastro.2006.12.031

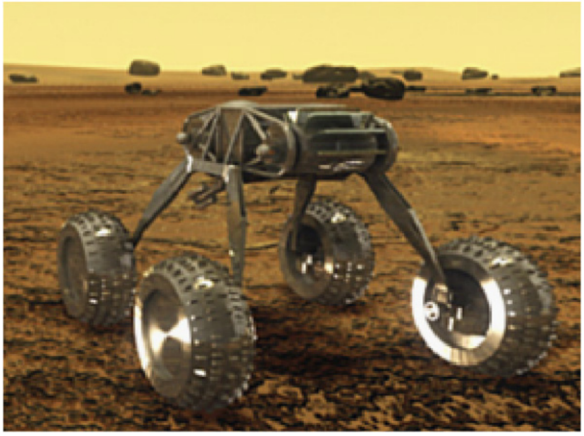

Fig. 1. Visualization of rover on Venus.

dioxide. The tops of Venus' mountains are slightly cooler: at the top of Maxwell Montes (10.4 km above mean elevation), pressure is 48 bar and temperature is only 390 °C (725 F). 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 SO_3, 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, with a spectrum weighted to longer wavelength (red). The light level is roughly equivalent to the illumination 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 atmosphere [7]. 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 elsewhere [8–11].

Fig. 1 is a conceptual design of the surface rover [7], 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.

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 [12,13] and dynamic (Stirling conversion [14]) options were analyzed. In addition to the power system, a Stirling refrigeration system was designed [15]. 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 [16,17], 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.

Lighter-than-air vehicles and airplanes were examined as platforms for the beaming station; airplanes were

Table 1
Power system trade-offs

Radioisotope power source	Demonstrated in space Dynamic [14] or thermoelectric [12,13] conversion approaches are possible 460 °C is a higher heat rejection temperature than conventional dynamic conversion approaches Radioisotope was chosen as the baseline technology for the Venus rover
Microwave beamed power	Station in atmosphere produces solar power; power is transmitted to surface by microwaves [18] Not demonstrated in Venus environment Many technical questions need to be answered Chosen as a backup approach—not analyzed in detail
Solar power	Solar power is difficult due to low light levels at surface [9] High temperature at surface makes photovoltaic conversion inefficient Approach would require new technologies to be developed [16]
Chemical (battery or fuel cell) storage	Requires high-temperature technology Practical approach for short missions or low powers

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 [18] 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.

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 [12]. 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.

Table 2
Performance of radioisotope thermoelectric converter (RTG)

Parameter	Value
Type	Thermoelectric
Power produced	30 W
T_{h}	1077 °C
T_{c}	600 °C
Conv. efficiency	5%
Input power Q_h	594 W
Heat rejected, Q_r	564 W

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 (Table 2).

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

2.3. Stirling power converter performance

For the Stirling converter case, Plutonium-isotope GPHS were baselined for the thermal power source to provide heat to the power converter. Each GPHS module provides 250 W 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 24 32.5 cm^2 vertical fins spaced around the circumference of the cold-side cylinder, for a total radiator area of 0.078 m^2. Using this radiator configuration, the predicted cold-side temperature is 500 °C, very close to the Venus ambient.

The Sage™ model [19] predicted a mechanical power output of 478 W, which slightly exceeded the required 469 W. The required heat input Q_h was 1740 W. 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 Ref. [20].

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 (Table 3). Ref. [20] 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 W, 100 W of electrical power are generated, and 280 W of mechanical power is

Table 3
Performance of radioisotope Stirling converter

Parameter	Value
Type	Stirling cycle
Power output	478 W
Source	7250-W GPHS units
T_h	1200 °C
T_c	500 °C
Heat input	1740 W
Heat rejected	1267 W
Overall efficiency	23.4%
Mass	21.6 kg

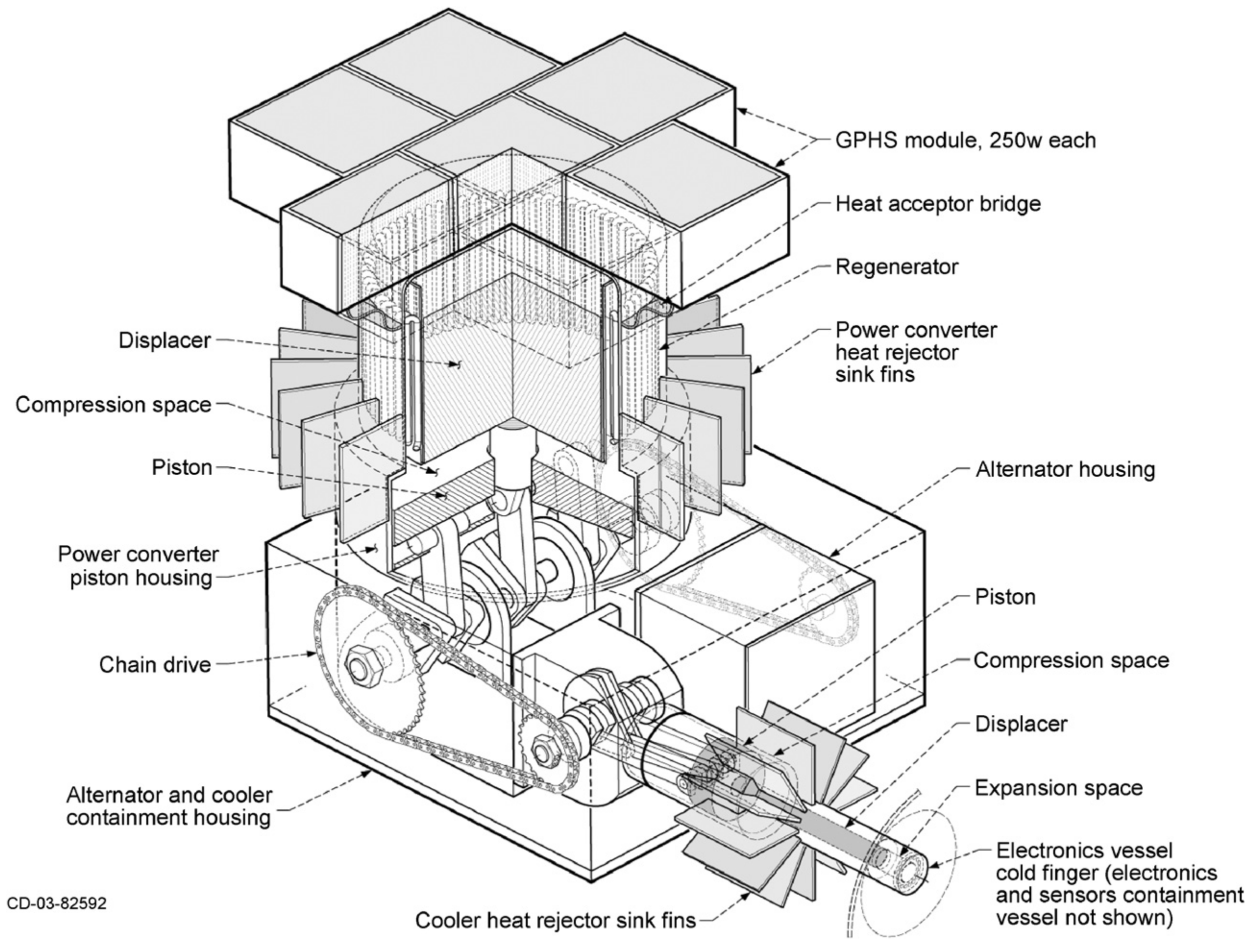

Fig. 2. Power converter and cooler.

available to be used for active cooling of the electronics enclosure [15]. 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.

2.4. Electrical power conversion

To produce electrical power from the mechanical power of the driveshaft of the Stirling engine requires 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 h [21]. 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 chosen. This technology, developed by the Air Force Research Laboratories, has been tested to 1250 F (675 °C) for 50 h.

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 that 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 Earth [22]. Fig. 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.

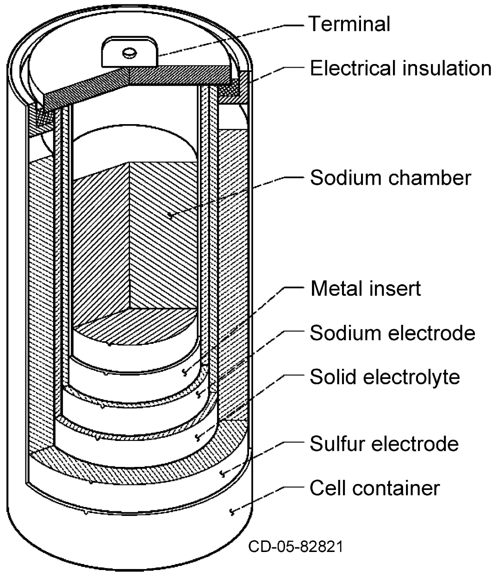

Fig. 3. Schematic of sodium–sulfur battery.

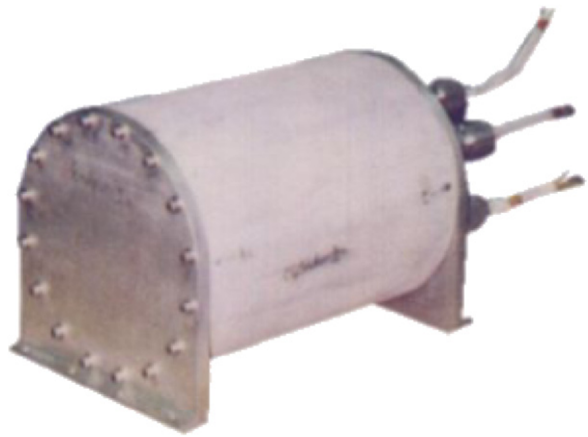

Fig. 4. Photo of sodium–sulfur battery flown on space shuttle.

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 350 °C) 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 (Fig. 4).

Typical operating temperature for terrestrial applications is 290–390 °C (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 460 °C.

Operation at 460 °C has been demonstrated at 92 bar pressure [22].

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/O_2 fuel cell [23], using a doped zirconia solid electrolyte [24]. 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 CO_2 as the source material.

The CO-O_2 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 600–1000 °C 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 300 °C, the maximum operating temperature of a high-temperature microcontroller to operate. The 400 W power system was sized to provide sufficient power to allow the refrigeration system to be run. (An alternate rover design was also analyzed [7], 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 W. With an estimated quantity of 10 W 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 W.

Table 4
Stirling cooler parameters

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

The design for a cooler system was selected to keep the operating temperature within the electronics enclosure under 300 °C, 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.

4.2. Cooler performance

A candidate Stirling cooler was designed and the performance analyzed using the Sage™ model [19]. The cooler was able to lift 105.7 W of heat from a cold sink temperature of 200 °C, and rejected 344.6 W of heat at a hot sink temperature of 500 °C. The required power input was 238.9 W. This gave an estimated thermodynamic coefficient of performance of 0.442 (The maximum theoretical coefficient of performance is 1.58.)

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 (Table 4). Ref. [25] summarizes technical details of the cooler.

5. Conclusions

A design study for a mission to investigate the surface and atmosphere of Venus [7] 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.

Acknowledgments

This study was funded by the NASA Revolutionary Aerospace Systems Concepts [26] Theme 1: "Looking for Life and Resources in the Solar system". A project like this is the sum of the work of a large number of people, and we would like to thank all the participants in the project. We would like to particularly acknowledge Al Juhasz for his contributions to the thermoelectric work, Marianne Rudisill (RASC 2004 Theme 1 manager) for the support of Langley, and Shawn Krizan for visualization.

References

[1] National Academies of Science Space Studies Board, New Frontiers in the Solar System: An Integrated Exploration Strategy, National Academies Press, Washington, DC, 2002.

[2] D. Crisp, et al., Divergent evolution among Earth-like planets: the case for Venus exploration, planetary decadal study community white paper, Solar System Exploration Survey, 2003–2013 2001.

[3] in: D.M. Hunten, L. Colin, T.M. Donahue, V.I. Moroz (Eds.), Venus, University of Arizona Press, 1983.

[4] in: S. Vougher, D. Hunten, R. Phillips (Eds.), Venus II, University of Arizona Press, 1997.

[5] D.H. Grinspoon, Venus Revealed, Perseus Publishing, 1997.

[6] J.B. Pollack, Atmospheres of the terrestrial planets, in: J.K. Beatty, A. Chaikin (Eds.), The New Solar System, third ed., Cambridge University Press, Cambridge, 1990, pp. 91–103.

[7] G. Landis, Robotic exploration of the surface and atmosphere of Venus, Acta Astronautica 59 (7) (2006) 517–580 paper IAC-04-Q.2.A.08.

[8] G.A. Landis, Exploring Venus by solar airplane, Presented at the STAIF Conference on Space Exploration Technology, Albuquerque NM, February 11–15, 2001. AIP Conference Proceedings, vol. 552, pp. 16–18.

[9] G.A. Landis, C. LaMarre, A. Colozza, Atmospheric flight on Venus: a conceptual design, Journal of Spacecraft and Rockets 40 (5) (2003) 672–677.

[10] G.A. Landis, C. LaMarre, A. Colozza, Venus atmospheric exploration by solar aircraft, Acta Astronautica 56 (8) (2005) 750–755.

[11] A. Colozza, Evaluation of solar powered flight on Venus, in: Second International Energy Conversion Engineering Conference, August 16–19, 2004, Providence, RI, paper AIAA-2004-5558.

[12] A. Chmielewski, RTGs for space exploration at the end of the 20th Century, in: 24th Intersociety Energy Conversion Engineering Conference 1989, Washington DC, vol. 2, August, 6–11, 1989, 715-720, paper IECEC-899237.

[13] W.A. Wong, Advanced radioisotope power conversion technology research and development, in: Second International Energy Conversion Engineering Conference, Providence, RI, August 16–19, 2004, NASA/TM-2004-213352; paper AIAA-2004-5515.

[14] R.K. Shaltens, L.S. Mason, J.G. Schreiber, Stirling radioisotope power system as an alternative for NASAs deep space missions, Forum on Innovative Approaches to Outer Planetary Exploration 2001–2020, Lunar and Planetary Institute, Houston TX, February 21–22, 2001, LPI-Contrib-1084, 76.

[15] G. Landis, K. Mellott, Stirling cooler for Venus exploration, Research and Technology 2003, NASA TM 2004-212729, 2004, pp. 49–50.

[16] G. Landis, P. Jenkins, D. Scheiman, R. Rafaelle, Extended temperature solar cell technology development, in: Second International Energy Conversion Engineering Conference, August 16–19 2004, Providence, RI, paper AIAA-2004-5578.

[17] G. Landis, R. Rafaelle, D. Merritt, High temperature solar cell development, Presented at the 19th European Photovoltaic Science and Engineering Conference, Paris France, June 7–11, 2004.

[18] W.C. Brown, The technology and application of free-space power transmission by microwave beam, Proceedings of the IEEE 62 (1) (1974) 11–25.

[19] D. Gedeon, Sage: Object-oriented software for cryocooler design, in: R.G. Ross Jr. (Ed.), Cryocoolers 8, Plenum Press, New York, 1995, pp. 281–292.

[20] K.D. Mellott, Power conversion with a Stirling cycle for Venus surface mission, in: Second International Energy Conversion Engineering Conference, August 16–19 2004, Providence, RI, paper AIAA-2004-5633.

[21] G. Montague, G. Brown, C. Morrison, A. Provenza, A. Kascak, High-temperature switched-reluctance electric motor, NASA Tech Briefs, February 2003, available as ⟨http://www.nasatech.com/Briefs/Feb03/LEW17287.html⟩.

[22] Fourth DOE/EPRI Sodium-Sulfur Battery Workshop, Mannheim, 1980.

[23] K.R. Sridhar, R. Förstner, Regenerative CO/O_2 solid oxide fuel cells for Mars exploration, AIAA Paper 98-0650, Reston, VA, 1998.

[24] K.R. Sridhar, B.T. Vaniman, Oxygen production on Mars using solid oxide electrolysis, Solid State Ionics 93 (1997) 321–328.

[25] K.D. Mellott, Electronics and sensor cooling with a Stirling cycle for Venus surface mission, in: Second International Energy Conversion Engineering Conference, August 16–19, 2004, Providence, RI, paper AIAA-2004-5610.

[26] M. J. Ferebee, Jr., R. A. Breckenridge, J. B. Hall, Jr., Revolutionary aerospace systems concepts—planning for the future of technology investments, in: 53rd International Astronautical Congress/2002 World Space Congress, October 10–19, 2002, Houston, TX, paper IAC-02-IAA.U.1.04.