Venus Mobile Explorer With RPS For Active Cooling: A Feasibility Study

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Abstract— We present our findings from a study to evaluate the feasibility of a radioisotope power system (RPS) combined with active cooling to enable a long-duration Venus surface mission. On-board power with active cooling technology featured prominently in both the National Research Council's Decadal Survey and in the 2006 NASA Solar System Exploration Roadmap as mission-enabling for the exploration of Venus. Power and cooling system options were reviewed and the most promising concepts modeled to develop an assessment tool for Venus mission planners considering a variety of future potential missions to Venus, including a Venus Mobile Explorer (either a balloon or rover concept), a long-lived Venus static lander, or a Venus Geophysical Network. The concepts modeled were based on the integration of General Purpose Heat Source (GPHS) modules with different types of Stirling cycle heat engines for power and cooling. Unlike prior investigations which reported on single point design concepts, this assessment tool allows the user to generate either a point design or parametric curves of approximate power and cooling system mass, power level, and number of GPHS modules needed for a "black box" payload housed in a spherical pressure vessel. Input variables include altitude, pressure vessel diameter, payload temperature, and payload power on Venus. Users may also specify the number and type of pressure vessel windows, use of phase-change material for additional (time-dependent) payload cooling, and amount of (rechargeable) battery power for peak power demand operations. Parameter sets that would enable a Venus surface mission with fewer than 16 GPHS modules were identified. Thus, the study provides guidance for design practices that might enable a long-duration Venus surface mission with an attainable quantity of ^{238}Pu, and with achievable operating parameters.[1]

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1. INTRODUCTION

The exploration of Venus is a challenging endeavor. In spite of its proximity to Earth, Venus presents an extreme environment of high pressure, high temperature, and chemically reactive atmosphere. Furthermore, the dense cloud cover on Venus prohibits the use of solar power near the surface. Nevertheless, Venus is an important target identified in both the National Research Council's Decadal Survey and in the 2006 NASA Solar System Exploration Roadmap. Missions such as a Venus Mobile Explorer, a Venus Seismic Network, or a Venus Lower Atmosphere Balloon Network may address fundamental questions about planetary habitability. Specifically, searching for evidence of past surface water on Venus and when it might have disappeared may elucidate what processes might have led Venus to lose its early habitability. [1].[2]

Prior missions to Venus have had lifetimes at the surface limited to a couple of hours due to limited battery life and the extreme atmospheric conditions. The Venera (7-14) and Vega (1 and 2) missions undertaken by the former Soviet Union successfully landed probes on the surface of

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Venus from 1970 through 1985, with the longest transmission time from the surface of 127 minutes from Venera 13. Venera 9 (and subsequent probes) utilized a system of circulating fluid to distribute the heat load in the payload pressure vessel. This system, plus pre-cooling via phase-change material prior to entry, permitted operation of the spacecraft for 53 minutes after landing. The U.S. Pioneer Venus Multiprobe of 1978 sent four probes into Venus' atmosphere, only one of which continued to send signals for approximately an hour after surface impact.

Although prior missions to Venus have provided valuable insight into the atmospheric conditions on Venus and *in situ* analysis of surface samples, long duration operation on or near Venus's surface – in excess of 90 days -- are necessary to fulfill the goals of NASA's Solar System Exploration Roadmap.

One of the principal technologies that will be needed to accomplish long-lived Venus surface exploration is the development of an on-board power source with active cooling for the payload. The demonstration of such a technology development might pave the way for future Venus sample return missions, and enable long-term studies of Venus.

Prior Studies and Conclusions

Several studies of power and cooling systems for long-lived Venus missions have been reported [2-5]. Uniformly, each has identified radioisotope heat source-driven Stirling power and cooling systems as the most promising concepts for Venus exploration.

In 1992, a Venus Interior Structure Mission (VISM) concept was presented at a Discovery Mission Workshop [2]. The VISM concept explored a mission architecture with three surface landers conducting seismology experiments. Each lander would contain a spherical pressure vessel and utilize a Stirling dynamic isotope power system and cooler. The study outlined a system point design with a 608 W-producing Stirling engine, a Stirling cooler that would require 557 W input power, and an alternator with required electrical power of 25 W (leaving a system energy margin of 26 W). The pressure vessel interior temperature was to be held at 300 K and Venus ambient environment was assumed to be 743 K. The study presumed a hot-end temperature of approximately 1450 K, corresponding to the temperature of the GPHS modules. Doing so led to an estimate of engine efficiency of 0.312.

While the VISM study provided a valuable point design, more recent calculations have been conducted at NASA Glenn Research Center (GRC) [3,4]. The latter calculations, based on thermodynamic simulations using the SAGE computer code of a kinematic Stirling engine and cooler, may provide more accurate estimates of Stirling generator and cooler efficiency and specific mass than those used in the VISM study.

The Stirling generator and cooler studies at GRC were conducted in 2004, and focused on a Venus lander mission application. However, as with the VISM study, these works provided a point design. Some of the parameters assumed were a 50-day lifetime at the surface, an electronics temperature of 573 K, and a heat source temperature of 1473 K.

Also in 2005, a Venus Rover study was conducted by JPL and Northrop Grumman Space Technology as part of a larger study on the application of advanced radioisotope power systems for solar system exploration entitled, "Extending Exploration with Advanced Radioisotope Power Systems" [5]. Two conceptual advanced Stirling generators were considered. The first was based on the Sunpower free-piston Stirling engine and linear alternator with an estimated efficiency of 32%, specific power of ~5.9 W_e/kg, and power output of ~80 W_e at the Beginning-Of-Mission (BOM). The second conceptual Stirling generator considered was specifically tailored for a long-duration Venus surface application. It is based on the Thermoacoustic Stirling Heat Engine (TASHE) with integrated pulse tube refrigerator (PTR) being designed by Northrop Grumman Space Technologies (NGST) and Los Alamos National Labs (LANL). The presumed payload pressure vessel internal temperature was under 323 K, with a surface lifetime of approximately 60 days. Unlike the spherical pressure vessels used on prior Venus missions and presumed in other Venus mission studies, the Venus Rover study considered the use of a cylindrical titanium pressure vessel of diameter 0.5 meter and length 1.5 meter with semi-spherical end caps. The largest subsystem power consumption was 260 W_e for surface mobility.

The Venus Rover study mission concept would have required 53 GPHS modules for the point design concept presented, corresponding to a ^{238}Pu mass of approximately 26.5 kg. Given present stores of ^{238}Pu, such quantities are not likely to be available.[6]

2. Purpose and Scope of Present Study

The purpose of this study was to provide information to the Venus Mobile Explorer Mission Concept Definition Team at JPL and other future Venus mission study teams on the feasibility of radioisotope power systems with active cooling for long-duration operation on or near the surface of Venus. Unlike prior investigations which reported on single point design concepts, the product of this study is a Microsoft Excel spreadsheet model that allows the user to generate either a point design *or* parametric curves of payload pressure vessel, cooling system, and power system mass as a function of altitude, pressure vessel diameter, payload temperature, and payload power on Venus. Users may also specify the number of pressure vessel windows (assumed to be sapphire) and window thickness, use of phase-change material for additional (time-dependent) payload cooling, and amount of (rechargeable) battery power for peak power demand operations. The model does not include any assumptions about the nature of the science, data, avionics, or communications instrumentation. We also completely neglect issues relating to cruise phase and entry, descent, and landing (EDL) operations and configurations; the model only applies to a Venus lander once it is on or near the surface. We do provide the ability to model metallic bellows mass in case an aerial mobility architecture is desired.

The model uses operating parameters for several different power system and cooler designs calculated from other studies. This study is not designed to advise on a down-selection between these concepts. It does, however, indicate the technology developments that would be needed to make each concept capable of fulfilling the Venus mission requirements.

Study Assumptions

The specific architecture for a Venus Mobile Explorer mission is undefined for this study. However, we assume that the payload is a "black box" contained within a spherical pressure vessel (either titanium or beryllium) that will remain within 15 km of the surface of Venus. An elevation of 5 km or less will be required for science observations. However, elevations up to 15 km may be used for mobility in a balloon mission architecture. Thus, the ambient atmospheric pressure will be between approximately 94 bar and 33 bar, and the temperature ranges between 460 ^{o}C (733 K) at the surface to 343 ^{o}C (616 K) at 15 km. We assume the payload would be cooled to a temperature between 40 ^{o}C (313 K) and 400 ^{o}C (523 K). A total mission operating time at Venus is presumed to be 90 days. System redundancy is not addressed; the cooling and power system is single-string.

GPHS modules are the heat source for the power system. The heat rejection temperature for the power generator is held at 40 degrees above the Venus ambient temperature. Because the science payload is undefined, no vibration requirements are presumed.

Previous studies have examined the use of Brayton and Stirling cycle generators, solar arrays, and TPVs, and concluded that Stirling cycle systems offered the most promise in terms of efficiency, reliability, and specific mass for a Venus surface application. Stirling systems in general offer the highest theoretical efficiency of any heat engine. Thus, we explore several Stirling system design concepts in the model: a kinematic Stirling generator with a linear-alternator-driven Stirling cycle cooler, a Thermoacoustic Heat Engine (TASHE) system with a pulse-tube cooler, and a free-piston Stirling generator and cooler concept. Each of the potential configurations has distinct advantages and disadvantages. For example, kinematic Stirling engines have been successfully developed commercially. However, kinematic Stirling systems have moving parts that introduce the potential for lower reliability. The TASHE system boasts the simplicity of fewer moving parts, yet has lower overall theoretical efficiency. The free-piston design also offers higher mechanical reliability than the kinematic Stirling generator concept.

Methodology

The model was developed in two parts. First, a heat leak model of the pressure vessel was created. It considers the heat load from the ambient Venus environment and that generated by the science payload. It determines the thermal power required to be lifted by the cooler unit. Temperature-dependent conduction and convection coefficients are calculated assuming the use of aerogel insulation [8]. Insulation thickness is a user-defined variable.

Next, for each Stirling concept considered, temperature-dependent values of generator efficiency and cooler coefficients of performance were taken from the associated studies. These values were used to estimate the input thermal power required to provide electrical power to the payload and operate the cooler via the generator. This value was then used to determine the required number of GPHS modules. Specific mass estimates, also identified from the design concept studies and scaled according to the generator and cooler hot-to-cold-end temperature ratios, were used to determine the lander mass without the payload or other subsystem masses.

3. Power and Cooling System Design

Pressure Vessel design

The pressure vessel design assumptions for the model are crucial because the choices of dimensions and insulation strongly affect the heat leak from the ambient environment. We assume the use of a spherical pressure vessel. The user may specify the diameter. On the graphs generated for this study, the diameter ranged between 0.5 m and 1.5 m. The pressure vessel can be composed of either beryllium or titanium with both external and internal insulation. The number of window ports, window diameter, and window thickness may also be user-specified. Each window is presumed to be composed of sapphire, thermally isolated from the pressure vessel walls, and heated (through resistive heaters) to the ambient Venus atmospheric temperature to avoid distortions in scientific observations.

Selected RPS Power and Cooling System Options

All Stirling configurations rely on the same concept of a closed-cycle regenerative heat engine with a gaseous working fluid. Stirling engines use the temperature difference between their hot ends and cold ends to establish a cycle of a fixed mass of gas, heated and expanded, and cooled and compressed, thus converting thermal energy into mechanical energy. The greater the temperature difference between the hot and cold sources, the greater the thermal efficiency. In practice, efficiency is limited by non-ideal properties of the working gas, and the engine material properties such as friction, thermal conductivity, tensile strength, creep, rupture strength, and melting point [9]. Table 1 shows the parameters of each Stirling concept considered.

Parameter	Kinematic Stirling [4,5]	TASHE with pulse tube cooler [6]	Free-piston Stirling concept [7]
Generator efficiency	$0.579*(1-T_C)/T_H$	$1-sqrt(T_C/T_H)$ (Curzon efficiency)	17% multiplied by T_C scaling factor from curve fits to data
Cooler efficiency	$0.28*T_C/(T_H-T_C)$	(T_H/T_C)^2 +1	
Generator specific mass	53 kg/kW_t	6 kg/kW_e	16.7 kg/kWe
Cooler specific mass	16 kg/kW	15 kg/kW	

Table 1 Stirling generator and cooler concept parameters

Both batteries and phase change material (PCM) provide important secondary power and cooling options for reducing overall RPS power requirements and allowing a cooling system alternative during some missions operations, specifically science data acquisition. Time-dependant models for both of these parameters are included in the model. The selection of PCM and associated properties is tied to the user-defined payload temperature.

The TASHE design concept

In the Thermoacoustic Heat Engine (TASHE), there are no moving parts (with the exception of an alternator for electrical power generation). Instead, pressure waves drive both a pulse tube cooler and linear alternator in parallel. The pressure and velocity fluctuations are such that heat is given to the oscillating gas at high pressure and removed at low pressure. The absence of pistons and drive mechanisms in the heat engine offers the potential of high reliability and long-term operation. The TASHE performance parameters and specific mass estimates were provided by NGST [11].

The Kinematic Stirling Power and Cooler Concept

The Stirling generator and cooler concept was derived from the kinematic Stirling cycle systems modeled at NASA Glenn Research Center (GRC) and described in the literature [3,4]. In the GRC studies, a point design was investigated with an assumed pressure vessel (electronics enclosure) internal temperature of 300 ^oC. The GRC design also assumed a cooler rejection temperature of 500 ^oC. We used the estimates of percent of Carnot efficiency, coefficient of performance, generator specific mass, and cooler specific mass in the model.

The Free-Piston Stirling Engine and Cooler Concept

NASA GRC provided performance estimates of several free-piston Stirling engine configurations specifically for this study [12]. Four configurations were considered. Separate cryocooler and Stirling power generation units were examined. Also, an integrated cryocooler and Stirling system (referred to as the duplex) was considered. Both variations were subdivided into options either with cooled magnets (inside the pressure vessel) or with magnets at ambient Venus atmospheric temperatures. Higher magnet temperature translates into lower converter efficiency, yet increases available payload volume in the pressure vessel. Ultimately, we incorporated the duplex model without cooling into the model.

4. RESULTS

The model was used extensively to evaluate the impact of various input parameters. Principally, it was used to determine what parameter space would enable a Venus surface mission with an amount of ^{238}Pu less than or equal to that used in two Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs). As each MMRTG utilizes eight GPHS modules, this corresponds to 16 GPHS units, or approximately eight kilograms of ^{238}Pu. Given current available quantities of ^{238}Pu, this was presumed to be an upper limit to what might be considered acceptable for mission feasibility. A summary of the findings follows.

Insulation

Insulation thickness is a parameter that can have significant impact on science instrumentation, as fields-of-view and required pressure vessel penetrations are effected. Although the code reflects temperature-dependent thermal conduction and convection, and state-of-the-art aerogel material properties were incorporated [ref], there was only moderate change in heat leak (and therefore cooling system mass and required system power) over the full range of pressure vessel operating temperatures. For example, outside insulation thickness ranging from 5 cm to 25 cm resulted in a change of two GPHS modules at a payload temperature of 100 °C.

Payload Temperature

Payload temperature over the range from approximately 100 °C to 400 °C had a relatively small effect on the overall system mass. That is to say that if a cooling system is required at all, only minor increases in its mass are necessary to address cooling over a large temperature differential. This finding potentially relaxes requirements for high temperature electronics if an active cooling system is present. Although recent technology developments have demonstrated long duration (~1700 hours) operation of silicon carbide-based electronics at temperatures of 500 ^{o}C [13], maintaining the internal temperature of the pressure vessel below 125 ^{o}C (to allow for use of conventional electronics) could be considered an option. For payload temperatures over 80 °C, the maximum GPHS number of 16 could be met as well, provided payload power was held below approximately 50 W.

Payload Power

The power dissipated by the payload inside the pressure vessel plays a disproportionately large role in defining the size of the power and cooling system. Every Watt of power needed to operate instrumentation and electronics must not only be generated, but then also must be removed, as it is thermally dissipated inside the pressure vessel. This places additional power demands on the cooling unit. For example, at a payload temperature of 100 °C, a 50 W payload power load would enable a mission with fewer than 15 GPHS modules, meeting the goal stated earlier. However, a 100 W payload power level would increase the number of necessary GPHS modules to over 20. In this example, we assumed a 1-meter diameter pressure vessel at the surface of Venus with an 850 °C hot-side temperature on a kinematic Stirling system.

Mission Altitude

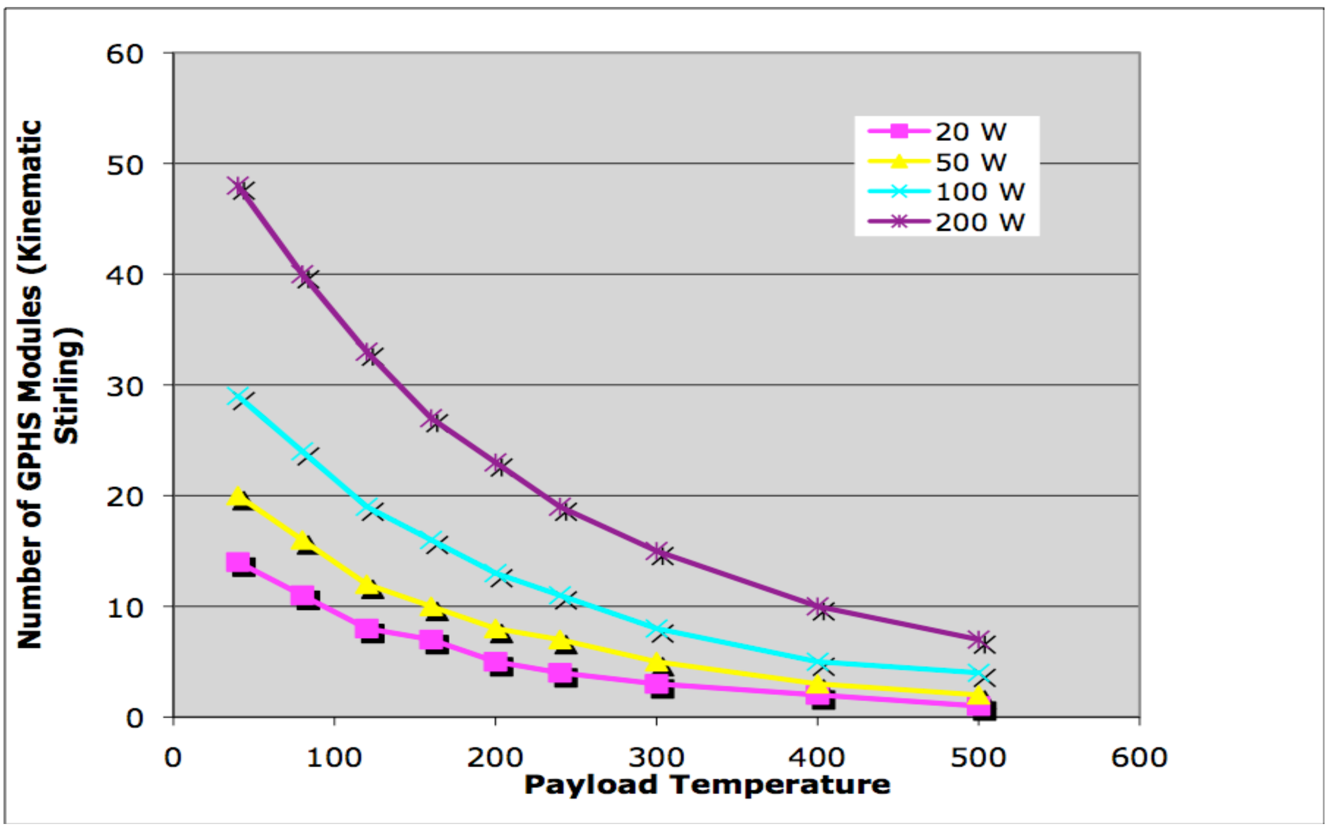


Figure 1 - Number of GPHS modules needed as a function of payload operating temperature and power. Simulation was performed for surface (altitude = 0), 850 C RPS hot-side temperature, and 1-meter pressure vessel diameter.

The model allows for simulated variation of science platform altitude up to 15 km above the surface. At higher elevations, the lower temperatures significantly reduce the heat transfer to the pressure vessel, resulting in a reduction in the required number of GPHS modules. Not surprisingly, this indicates a favorable architecture would be one in which science that needed to be conducted at the surface could be accomplished during brief excursions, where batteries and Phase Change Materials (PCMs) supply the additional cooling needed. Upon returning to higher elevations, both batteries and PCMs could be recharged/regenerated by the RPS system.

A table of the phase change materials used in the model is shown below. The model selects the PCM closest to the user-specified payload temperature.

generator is hot-end temperature, as this parameter dictates maximum (Carnot) efficiency. Figure 2 shows the number of GPHS modules needed to provide the cooling power for payloads of temperatures ranging up to 400 °C for a variety of hot-end temperatures. All RPS concepts considered in the model have a hot end temperature that could be user-specified between 650 °C and 1300 °C. However, state-of-the art Stirling systems are limited to hot end temperatures of between 850 °C and 900 °C with the use of MarM-247 alloy [6]. Higher temperatures result in materials creep that compromises the seals in Stirling generators. Significant technology development work would be required to increase hot end temperatures beyond this. Nevertheless, at a hot-end temperature of 850 °C, solutions could be found for the Plutonium-limited condition.

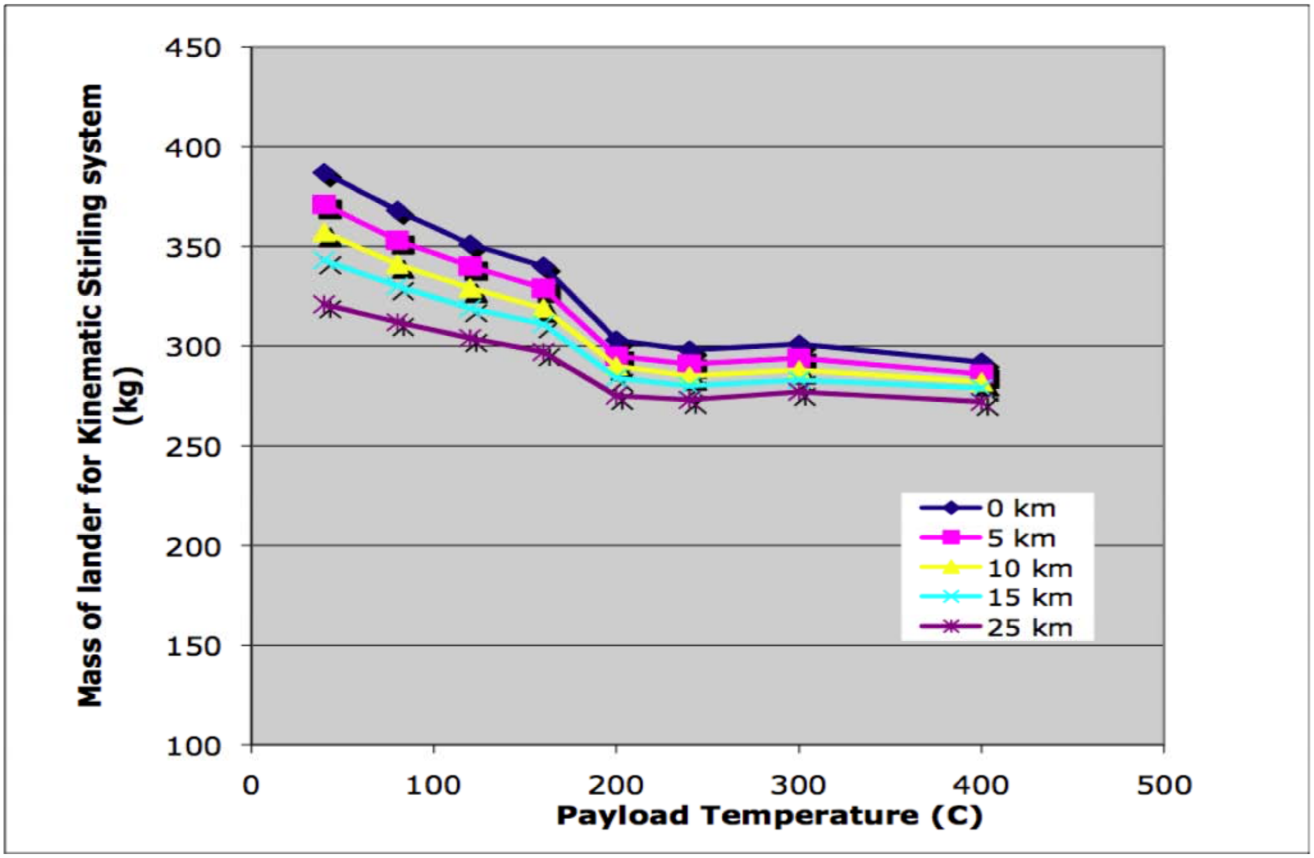


Figure 2 - Mass of Kinematic Stirling lander (power, cooling, and pressure vessel) as a function of payload temperature and mission altitude. Other parameters are GPHS hot-end temperature of 850 C, 1-meter diameter pressure vessel.3

Material	Melting Point (°C)	Latent Heat (kJ/kg)	Density of Solid kg/m3)
Sodium	97.7	115	968
Lithium	180.5	664	534
$LiNO_3$	253	370	2380
$NaNO_2$	284	200	2170
$NaNO_3$	306.5	180	2261

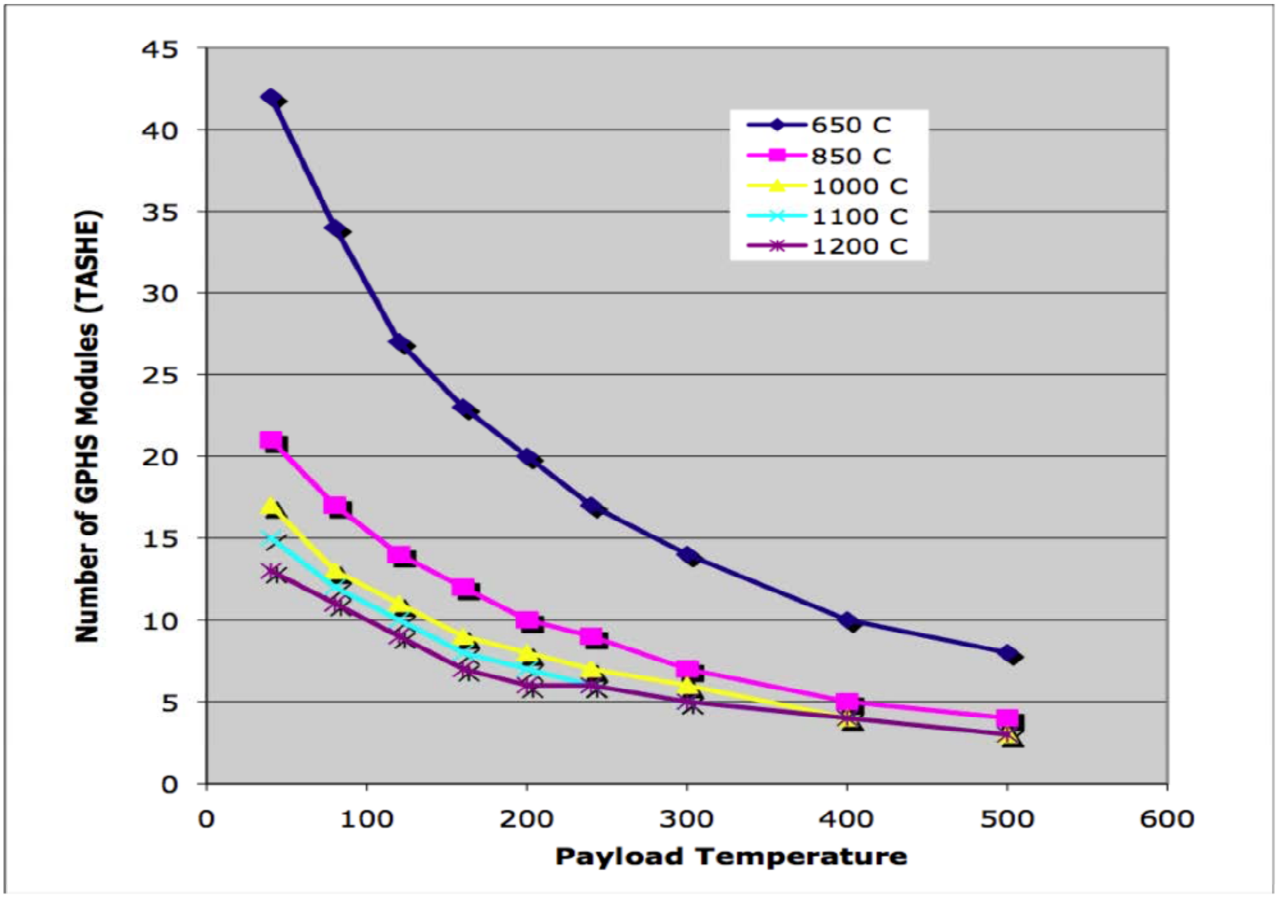
Table 2 - Phase Change Material (PCM) look-up table used in the model.

RPS Design

One of the most important design considerations for the generator is hot-end temperature (see above).

5. Example Architecture: Venus Mobile Explorer with Metallic Bellows for Aerial Mobility

The mass of metallic bellows for an aerobot mission can be scaled as a function of altitude and payload mass (up to 15 km) [8] to be used in concert with the power and cooling system mass to determine feasibility of a balloon



architecture for a given range of input variables.

Figure 3 - Number of GPHS modules needed for the TASHE system as a function of payload temperature and RPS source hot-end temperature. Simulation was performed for surface (altitude = 0), 50 W payload power, and 1-meter pressure vessel diameter.

6.

These data shown in Figure 4 provide an estimate of bellows size for a maximum Venus float altitude of 15 km, where the density of the atmosphere is 45% less than at 5 km altitude. Balloons at 5 km would therefore be only 55% of the volume as shown in the figure, and the mass, which is proportional to surface area, would be about 67% of the mass shown.

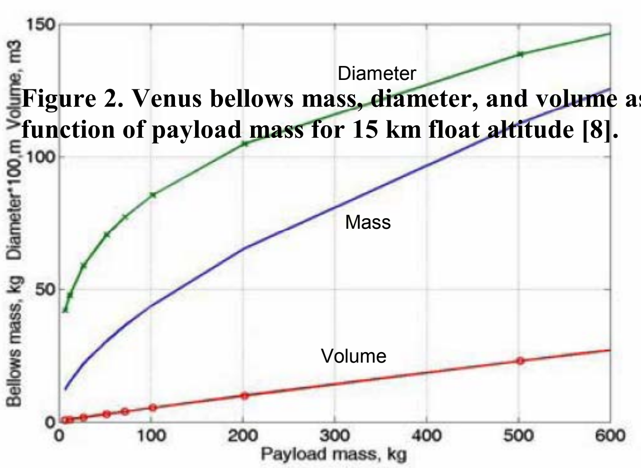


Figure 2. Venus bellows mass, diameter, and volume as a function of payload mass for 15 km float altitude [8].

Conclusions and Future Work

We developed a modeling tool to examine the impact of a large number of system parameters on the mass and power of a long-lived Venus surface mission with active cooling. The tool offers flexibility in evaluating system trades for a Venus mission unlike those reported previously. The model was useful in identifying design features that could potentially enable a Venus mission utilizing an obtainable quantity of ^{238}Pu. Further, it provides insight into the relative benefits of advances in Venus mission-related technologies.

The algorithm developed for the Venus mission model potentially lends itself to applications in the study of a larger class of space science missions. Specifically, missions in other extreme environments may be modeled similarly by simply modifying the environmental segments of the model (e.g. changing atmospheric density and temperature profiles) and removing or replacing the cooling segment with other destination-specific systems. Development of such a generalized tool may provide a useful mechanism for evaluating mission architecture trades for other destinations in the solar system.

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REFERENCES

[1] NASA Solar System Exploration Roadmap, September, 2006 http://solarsystem.nasa.gov/multimedia/downloads/SSE_RoadMap_2006_Report_FC-A_med.pdf.
[2] E. Stofan, R. Saunders, "Venus Internal Structure Mission (VISM)", Discovery Missions Workshop Concept Number 81, Pasadena, California, September 1992.
[3] K. Mellott,, "Electronics and Sensor Cooling with a Stirling Cycle for
Venus Surface Mission", AIAA 2004-5610, 2nd International Energy Conversion Engineering Conference, Providence, Rhode Island, August 2004.
[4] K. Mellott, " Power Conversion with a Stirling Cycle for Venus Surface Mission", AIAA 2004-5622, 2nd International Energy Conversion Engineering Conference, Providence, Rhode Island, August 2004.
[5] R.D. Abelson, T.S. Balint, M. Evans, T. Schriener, J. H. Shirley, T. R. Spilker, "Extending Exploration with Advanced Radioisotope Power Systems", JPL D-28903, PP-266 0333, November 2005.
[6] nuclear.inl.gov/spacenuclear/docs/**final72005faqs**.pdf
[7] D. J. Anderson, J. Sankovic, D. Wilt, R. D. Abelson, J. Fleurial, "NASA's Advanced Radioisotope Power Conversion Technology Development Status", NASA/TM—2007-214487, April, 2007.
[8] S. Distefano, JPL, Personal Communication, March 2008.
[9] V. Kerzhanovich, J. Hall, A. Yavrouian and J. Cutts, "Two Balloon System to Lift Payloads from the Surface of Venus," AIAA-2005-7322 AIAA 5th ATIO and16th Lighter-Than-Air Sys Tech. and Balloon Systems Conferences, Arlington, Virginia, Sep. 26-28, 2005.
[10] http://en.wikipedia.org/wiki/Stirling_engine
[11] M. Petach, NGST, Personal Communication, March 2008.
[12] P. Schmidt, NASA GRC, Personal Communication, September 2007.
[13] NASA Press Release 07-189, "NASA Researchers Extend Life of Hot Temperature Electronic Chip", September 2007.

BIOGRAPHY

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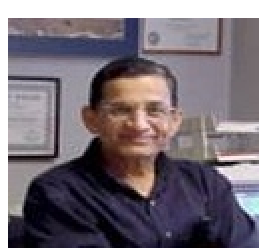

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