Thermal Management System for Long-Lived Venus Landers

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Long-lived Venus Landers require cooling, which can be provided with a radioisotope power converter and cooling system. Heat from a stack of General Purpose Heat Source (GPHS) modules must be delivered to the Stirling convertor with minimal ΔT. In addition, the cooling system must be shut OFF during transit to Venus without overheating the GPHS modules. The bypass heat can be removed by alkali metal Variable Conductance Heat Pipes (VCHPs) integrated with a two-phase heat collection/transport package (HTP) from the GPHS stack to the Stirling convertor. A five-feature flat-front-theory-based VCHP model was developed, and a four-feature proof of concept VCHP was designed, built and successfully tested. The five-feature VCHP model predicts that the Stirling convertor can: 1) rest during transit at ~100°C lower temperature than the nominal one (~1000°C); 2) pre-cool the modules before the entry into the Venus atmosphere, lowering the temperature by another ~85°C; 3) work at nominal temperature of ~1000°C on Venus surface; 4) stop working (for short periods of time on Venus surface with a relatively small vapor temperature increase of ~ 6-9°C and 5) reject excess heat during the entire mission if short-lived isotopes are used. The four-feature proof of concept test setup was a sodium-stainless steel VCHP. Proof of concept theoretical and experimental results for the Backup Cooling System are presented in this paper. The experimental data fully validated the model.

Nomenclature

$D_{mission}$	total duration of the mission [days].
HL	half-life of the isotope (HL = 138 days for Po-210).
IDc	internal diameter of the condenser
Lc	length of the condenser (the front can move only within this domain along the entire mission)
N_{VCHP}	number of VCHPs
P_N	nominal power [W] required by the main Stirling.
P_{rej}	instantaneous power rejected by the VCHP radiator along the mission
Tv1, Tr1	steady state vapor and reservoir temperatures during transit (feature 1)
Tv2, Tr2	steady state vapor and reservoir temperatures after pre-cooling (feature 2)
Tv3, Tr3	steady state vapor and res. temperatures during normal operation on Venus (feature 3)
Tv4, Tr4	steady state vapor and reservoir temperatures after stoppage on Venus (feature 4)
c_1	proportionality constant that includes rejection thermal resistance in space.
c_2	proportionality constant that includes rejection thermal resistance on Venus and is chosen arbitrarily.
x_{front}	front location in the condenser with respect to the beginning of the condenser (vapor side).

Acronyms

ASRG	Advanced Stirling Radioisotope Generator
BOM	Beginning of Mission
BON	beginning of normal operation
BOP	beginning of pre-cooling

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BOT beginning of transit
CAD Computer Aided Design
EOM End of Mission
EON end of normal operation
EOP end of pre-cooling
EOT end of transit
GPHS General Purpose Heat Source
HTS Heat Transport System
HTTMS High Temperature Thermal Management System
NCG Non Condensable Gas
SC Stirling Converter
TC Thermocouple
VCHP Variable Conductance Heat Pipe

I. Introduction

The thermal management system for a Long-Lived Venus Lander is critical for the mission success. The difficult operating environment on Venus, 460°C and 9.3 MPa pressure, presents significant thermal design and implementation challenges. None of the previous missions operated for more than two hours on the Venus surface. For a greater science return, missions with longer operating duration on the Venus surface are needed. Dyson (2009) has proposed a Stirling system that generates power as well as provides cooling to allow the lander's instruments to survive for more than one year in the harsh environment of the Venus surface. It consists of a multi-stage cooling system using several Stirling systems, and an energizing radioisotope Stirling power converter that is coupled (electrically or pneumatically) to the Stirling coolers. During operation, high temperature (~1000°C) heat is supplied from a stack of General Purpose Heat Sources (GPHS) to the main (energizing) Stirling convertor.

The radioisotope based GPHSs must be cooled to prevent overheating when the Stirling convertor is shut OFF (briefly on Venus, or for longer periods during transit). This bypass heat must be collected from the GPHSs at around 1000 - 1200°C. If short-lived radioisotopes are used the GPHSs supply more heat than is required. This excess heat must also be collected at about 1000°C, and continuously rejected into both space during transit and the Venus environment during normal operation. A High Temperature Thermal Management System (HTTMS) was developed to supply heat to the Stirling convertor. It consists of a heat transport system (HTS) from the multi-GPHS stack to the Stirling convertor, and a Backup Cooling System. These two subsystems are integrated to form a continuous vapor path from the GPHS modules to the convertor's heater head. The backup cooling system uses Variable Conductance Heat Pipes (VCHPs) to passively reject the bypass and/or the excess heat from the GPHS modules. Proof of concept theoretical and experimental results for the Backup Cooling System are presented in this paper.

II. Background – Variable Conductance Heat Pipes

A simple VCHP is shown below in Figure 1. It is similar to a conventional heat pipe but has a reservoir and controlled amount of non-condensable gas (NCG) inside the reservoir. When the heat pipe is operating, the NCG is swept toward the condenser end of the heat pipe by the flow of the working fluid vapor. The NCG then blocks the working fluid from reaching a portion of the condenser. The VCHP works by varying the amount of condenser available to the working fluid. As the evaporator temperature increases, the vapor temperature (and pressure) raises, the NCG compresses (Figure 1 top) and more condenser is exposed to the working fluid increasing the conductivity of the heat pipe and driving the temperature of the evaporator down. Conversely, if the evaporator cools, the vapor pressure drops and the NCG expands (Figure 1 bottom) reducing the amount of available condenser, decreasing the heat pipe conductivity, and driving the evaporator temperature up.

In contrast to the conventional VCHP as shown in Figure 1, the current VCHP has two different heat rejection surfaces. One surface supplies heat to the Stirling convertor, while the other is used to dump the heat from the GPHS modules when the energizing Stirling is OFF.

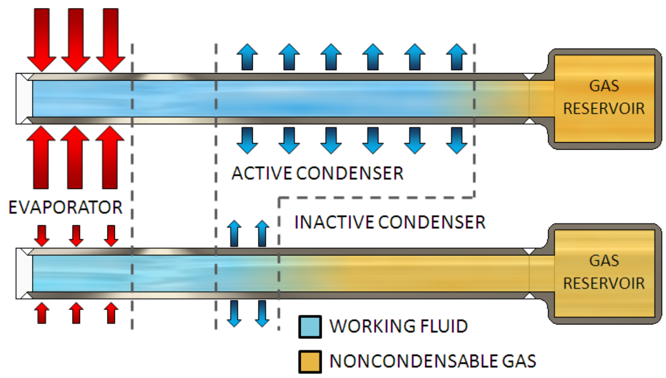


Figure 1. The working of a variable conductance heat pipe (VCHP) is illustrated. At high heat load the temperature dependent saturation pressure of the working fluid is high and compresses the non-condensable gas (NCG) into the reservoir. At lower heat input the working fluid temperature and pressure is lower, and the NCG expands into the condenser.

III. Variable Conductance Heat Pipe for Long-Lived Venus Landers

The high temperature VCHP will provide backup cooling for the GPHS modules during various contexts encountered along the mission. These contexts determined the VCHP "features" and they are briefly presented below in two configurations:

Four- feature configuration - if Pu-238 is used:

1. *Feature 1* (Transit): The system will operate (allowing the convertor to rest) during transit at a lower temperature (120-150K lower) than nominal.
2. *Feature 2* (Pre-Cooling): The GPHS modules can be pre-cooled before re-entry into the Venus atmosphere.
3. *Feature 3* (Operation on Venus): When the reservoir temperature becomes equal to that on Venus, the system will passively increase its vapor temperature and the convertor will start working at the nominal temperature.
4. *Feature 4* (Stoppage on Venus): Multiple brief stoppages of the system can occur on Venus.

Five-feature configuration - if alternative isotopes with shorter half-life are used instead of, or in combination with Pu-238 then an additional feature is introduced:

5. *Feature 5* (Excess heat removal): If the alternative isotopes have a significantly shorter half-life, then any power supply configuration, totally or partially based (hybrid) on alternative isotopes, will need to be oversized at the beginning of the mission (BOM). Consequently, the excess heat must be removed continuously between the beginning of the mission and the end of the mission (EOM). This feature will be also done by the VCHP, superimposed on the other four features.

The four-feature VCHP was demonstrated theoretically and experimentally for the case when Pu-238 is used as fuel. The fifth feature was demonstrated only theoretically for the case when short-lived isotopes are used as fuel and decaying excess heat must be continuously rejected. This paper presents the experimental results for the proof of concept testing of the four-feature concept and theoretical results for the five-feature concept.

A. Four Feature VCHP Concept

The four-feature configuration VCHP concept is described below based on the schematic presented in Figure 2:

- Figure 2a shows the Stirling convertor stopped (during transit to Venus) while the VCHP is working. The reservoir is ***cold***, which allows the vapor–non-condensable gas front to retreat beyond the second condenser, so that the GPHS heat is dumped from the radiator to the cold side adapter flange and further into the environment. The vapor temperature in this case is significantly lower than the nominal working temperature on Venus, saving heater head life.
- Figure 2b shows the convertor under operation at a lower temperature set-point to pre-cool the GPHS modules (and all the other components) before re-entry in the Venus atmosphere. The VCHP is OFF so, in this case, the front is located somewhere between the first condenser (heater head) and second condenser despite the ***cold*** reservoir (exposed to deep space). The heater head now accepts the heat from the GPHS

modules and the vapor temperature is lower than the transit vapor temperature. This vapor temperature is in fact the lowest among all four features. However, it does require the Stirling to operate.

- Figure 2c shows the convertor under normal operation (on Venus) while the VCHP is OFF with a ***hot*** reservoir. In this case, the front is located somewhere between the first condenser (heater head) and second condenser. This context occurs because the reservoir heats up when exposed to the Venus environment, allowing the NCG gas to block the radiator while the heater head accepts the heat. The vapor temperature in this case is the nominal working temperature on Venus (1100-1200°C).
- Figure 2d shows the Stirling convertor stopped (on Venus) while the VCHP is working. In this case, the heater head does not accept heat, which increases the vapor temperature and pressure pushing the gas front beyond the radiator, despite the ***hot*** reservoir. The steep vapor pressure of sodium in this temperature range creates the ideal conditions for this feature because the required temperature increase to shut OFF the Stirling is very small (a few degrees) which is highly desirable.

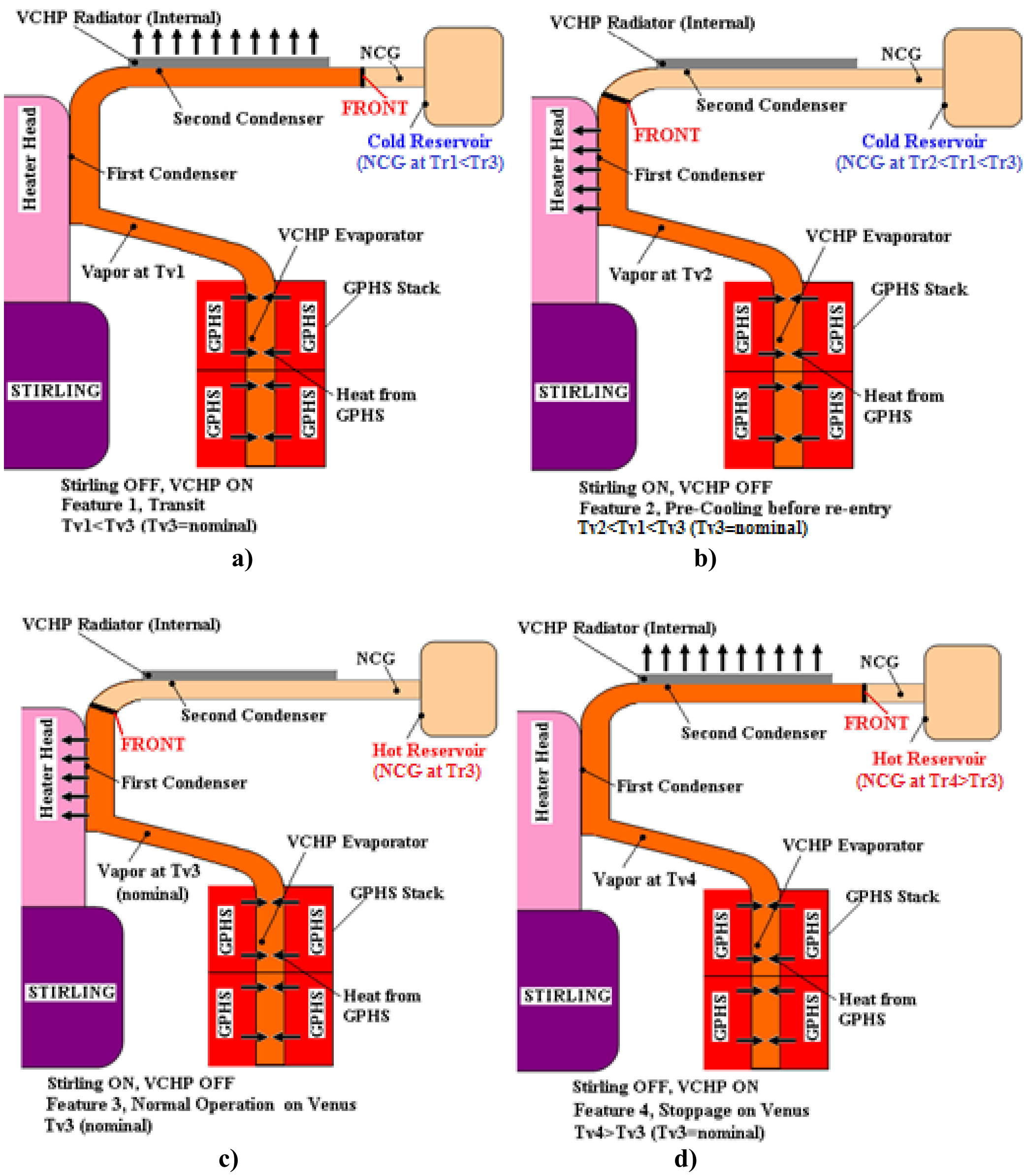


Figure 2. Schematic of principle for the Backup Cooling System of the HTTMS: four-feature VCHP concept a) Stirling OFF during transit to Venus with a cold reservoir. b) Pre-cooling the GPHS modules before re-entry. c) Stirling operating on Venus with a hot reservoir. d) Stirling convertor stopped on Venus. The symbols and acronyms used in this figure are described in the Nomeclature and Acronyms sections of this paper.

As seen in Figure 2, the GPHS modules are thermally connected to the heater head just by one vapor space (heat pipe) and its adjacent wall with no other interface being employed. Consequently, the temperature drop between the GPHS modules and the heater head will be minimal because of the low thermal resistance that this configuration allows.

B. Five Feature VCHP Concept

The opportunity of using more accessible isotopes that have shorter half-lives was also considered. Since it may have a great impact on the overall development of the HTTMS, the feasibility of this opportunity was analyzed. The significantly shorter half-life of the accessible isotopes implies that the initial power is much higher than required. Since sufficient power must be available at the end of the mission, excess heat is available during the entire mission. This heat must be continuously and passively rejected while maintaining the appropriate temperature and power at the heater head.

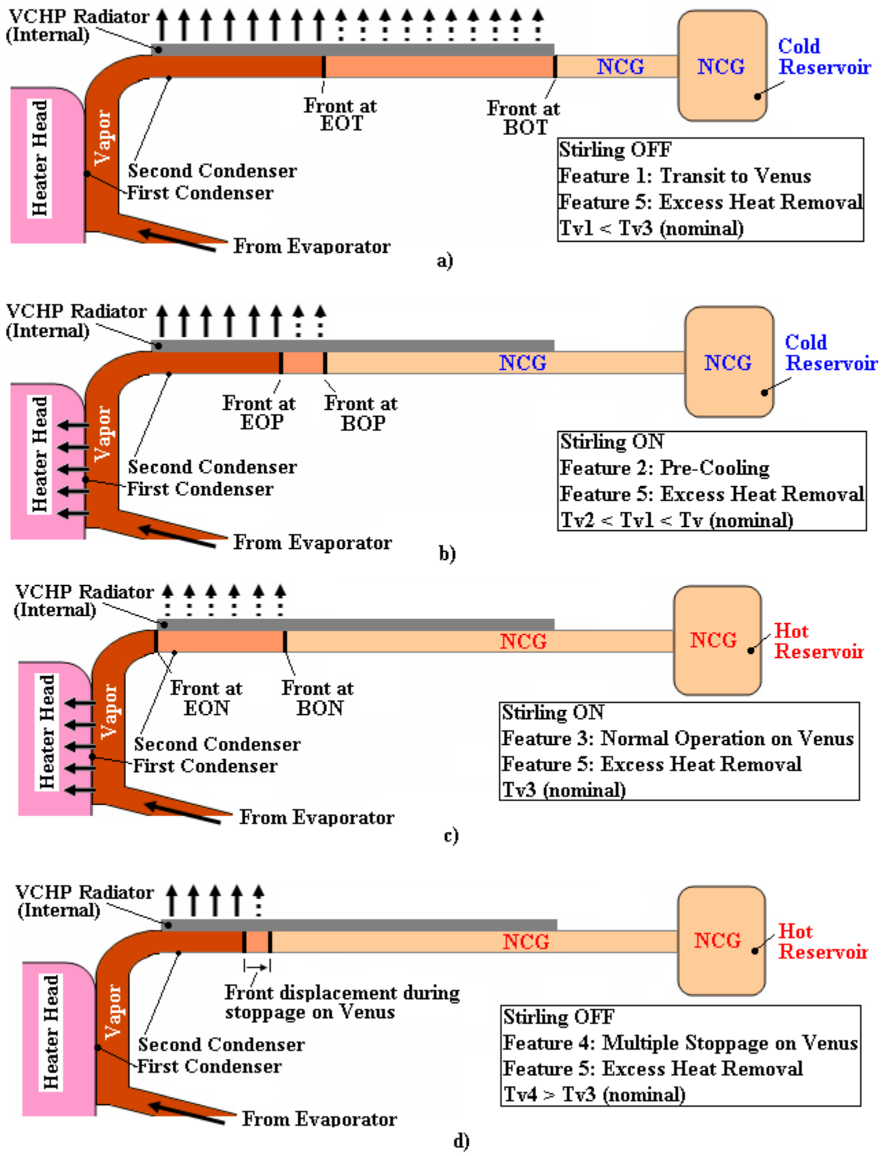
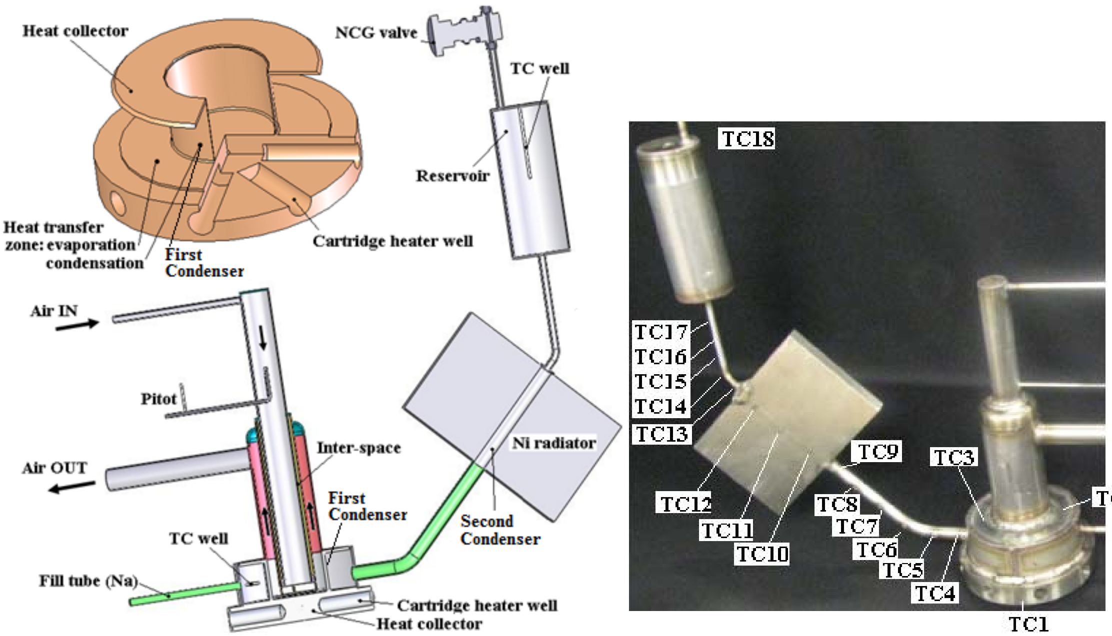


Figure 3. Five feature VCHP – concept: a) Transit to Venus with excess heat removal (Features 1 and 5), b) Pre-cooling with excess heat removal (Features 2 and 5), c) Normal operation on Venus with excess heat removal (Features 3 and 5), d) Stoppage on Venus with excess heat removal (Features 4 and 5). The symbols and acronyms used in this figure are described in the Nomeclature and Acronyms sections of this paper.

The VCHP integrated with the HTTMS of the Long Lived Venus Lander has the capability of continuous removal of the excess heat generated by the alternative isotopes with shorter half-life. This capability represents the ***fifth feature*** of this VCHP and works superimposed on the other four features described above. The five-feature VCHP concept is presented above in Figure 3 while its theoretical demonstration is discussed later in the paper.

IV. Reduced Scale System Design – Test Setup to Demonstrate the Four Feature VCHP

Based on the four-feature configuration VCHP model, a reduced scale test setup for concept demonstration was designed and fabricated; see Figure 4. The nominal temperature designated as "operating on Venus" (or the "working point") was reduced for this preliminary experiment to simplify fabrication, since it allowed the use of stainless steel, rather than the more expensive superalloys and refractory metals. The plots presented in Figure 5 show the vapor temperatures for all four features as a function of the working point, Tv3. As seen, the working point was set at 850°C as a design requirement while all the other temperatures result. Results for other two working points (nominal temperatures), 780ºC and 820ºC, are summarized in the end of the paper.



a) b)

Figure 4. a) Proof of concept test setup – CAD model b) Experimental test setup – thermocouple locations.

The design parameters are presented in Table 1. A CAD model of the proof of concept test setup is shown in Figure 4a while the fabricated one is shown in Figure 4b. An enlarged view of the heat collector is shown in the upper side of Figure 4a. The cartridge heaters are installed in radial configuration delivering heat volumetrically except for a one inch diameter cylinder in the center. The center is not heated because the heat is removed from the sidewalls, not from the center of an actual Stirling system.

For the same reason, a spacer (not shown) was installed at the bottom of the heater head simulator to create an air gap as an insulator. Although thermocouple wells are shown only in the reservoir and evaporator (in the heat collector), the entire length of the VCHP had intrusive thermocouples to measure the temperature distribution and detect the vapor-NCG front location. The reservoir is provided with band heaters (not shown) that allow the reservoir to reach the desired temperatures. The heat provided by the cartridge heaters is further conducted by the nickel heat collector to the evaporation surface. Most of the heat is carried to the heater head interface through the vapor which condenses at the inner cylindrical surface. The heater head simulator uses air flow as coolant (simulating an operating Stirling) where the air flow rate is monitored with a Pitot tube. The black arrows in Figure 4a show the air-flow path. Air flows down the center tube, then past the section marked "First Condenser", where the heat from the heater cartridges is removed, and then is exhausted.

Figure 4b shows the locations of the thermocouples that are used to plot the temperature profiles along the VCHP. All of these thermocouples are intrusive, inserted into thermo-wells. Thermocouple TC1 is the only one that is not measuring a fluid (vapor or NCG) temperature. It measures the highest temperature in the system since it is inserted in the center of the heat collector, underneath the heat pipe, where the heaters converge in radial direction. Thermocouples TC2 and TC3 measure the vapor temperature in the evaporator. Thermocouples TC4 through TC 9 measure the temperature profile (front location) along the evaporator-condenser connecting tube. Thermocouples TC10, 11 and 12 measure the temperature profile along the second condenser/radiator. Thermocouples TC13 through 17 measure the temperature profile along the VCHP second condenser-reservoir connecting tube while thermocouple TC18 measures the reservoir temperature (the thermo-well allows the thermocouple to deep into the reservoir along the central axis at the middle of the reservoir height).

Table 1. Design parameters and material properties for the experimental VCHP.

Parameter	Value
Power to be conducted by the VCHP	1000 W
VCHP material	SS304
Heat collector material	Ni201
Radiator material	Ni201
Screen material	SS304 (100x100)
Vapor temperature during normal operation on Venus, Tv3	850°C
Vapor temperature during transit, Tv1	789.6°C
Vapor temperature after pre-cooling before re-entry, Tv2	772°C
Vapor temperature during stoppage on Venus, Tv4	855.4°C
Reservoir minimum temperature (after pre-cooling), Tr2	27°C
Reservoir maximum temperature (during stoppage), Tr4	465°C
Reservoir temperature during transit, Tr1	100°C
Reservoir temperature during normal operation on Venus, Tr3	460°C
Number of moles of NCG	0.003035 moles
Height of the heat transfer area of the heater head	1.2 in

Operation - The power applied to the heaters must include both the losses to the ambient and the actual power (1 kW) that is consumed by the convertor. First, the losses are determined for the nominal temperature of 850°C so, the applied power is incrementally increased with no cooling until steady state is reached at 850°C. The necessary air-flow rate is determined similarly but with a total applied power equal to the sum between the losses and the nominal power while the air-flow rate is adjusted to obtain steady state at 850°C. When steady state is reached, the front should be located at the exit of the evaporator for a reservoir temperature equal to Tr3=460°C. The measurements start with the first feature (transit) and go through all four by turning ON and OFF the air cooling while adjusting the reservoir temperature accordingly using band heaters.

V. Four-Feature Concept: Testing Procedure

The four-feature configuration system was tested for three different nominal working temperatures on the Venus surface: 780°C, 820°C and 850°C (the set-point temperature was changed by adjusting the amount of NCG).
For clarity, a nomenclature of the temperatures involved along the four features is presented below:

- Tv1, Tr1 – steady state vapor and reservoir temperatures during transit (feature 1)
- Tv2, Tr2 – steady state vapor and reservoir temperatures after pre-cooling (feature 2)
- Tv3, Tr3 – steady state vapor and res. temperatures during normal operation on Venus (feature 3)
- Tv4, Tr4 – steady state vapor and reservoir temperatures after stoppage on Venus (feature 4)

The system was tested in the order of the occurrence of the 4 features as follows:

- Feature 1 (Transit): Represents the temperature distributions during transit. 1200W of power were applied gradually to bring the entire system to the steady state that corresponded to transit (feature 1). For this context, the reservoir was also heated to raise its temperature to Tr1. The cooling was OFF (simulated Stirling convertor was OFF). Figure 7 shows the pre-cooling (the transition from feature 1 to feature 2).

- Feature 2 (Pre-Cooling): Represents the steady state after pre-cooling before entry. The 1200W of power, simulating the GPHS modules, was maintained throughout the entire experiment. The only intervention was turning the compressed air ON and OFF (simulating the Stirling convertor) and heating or cooling the reservoir to reach the design temperatures. So, for pre-cooling, the cooling was turned ON (Stirling was started) and the reservoir cooled to Tv2. The cooling rate was adjusted (monitoring it with the Pitot tube) until steady state was reached. This cooling rate was subsequently used throughout the experiment to simulate a working Stirling. The steady state at the end of pre-cooling gives the temperatures that correspond to feature 2, Tv2 and Tr2.
- Feature 3 (Normal Operation on Venus): Represents the steady state on Venus surface when Stirling is under normal operation. Figure 8 shows the entry, landing and reaching steady state under normal operation on Venus; in other words, the transition from feature 2 to feature 3. Cooling was turned OFF while the reservoir heating started. Since the front quickly moved toward the radiator involving an increase in temperature (faster than the reservoir increase in temperature), when this temperature reached Tv4 (the maximum allowed temperature of the heater head resulted from feature 4), the cooling started to simulate a working Stirling on Venus surface. During this time, the reservoir kept increasing in temperature while the evaporator started to slowly cool down from Tv4 to Tv3, the nominal value, while the front started to retract toward the evaporator. The system eventually reached near steady state when Tv3 and Tr3 reached their predicted values. So, at the end of this feature, the cooling is ON (convertor ON), the VCHP is OFF while the reservoir is heated.
- Feature 4 (Stoppage on Venus): Represents stoppage on Venus. Figure 9 shows the transition from feature 3 to feature 4. At this point, maintaining the same temperature of the reservoir, the air cooling is turned OFF to simulate turning OFF the Stirling. The front exits the evaporator and advances toward the second condenser where stops under a new steady state (heat is now rejected by the second condenser). Now, the evaporator temperature is Tv4 slightly higher than Tv3, the nominal working temperature.
- Back to feature 3 (Normal Operation on Venus): Simulates Stirling restart on Venus (Figure 10). The compressed air cooling is turned ON again and the front starts to retract while the evaporator (heater head) temperature decreases to Tv3. The reservoir temperature is maintained constant (Tv3~Tv4). When the new steady state is reached, the nominal temperature corresponding to the normal operation on Venus is reached and this is, again, feature 3.

VI. Four-Feature Concept: Experimental Results

Next, the experimental results are presented only for the 850°C nominal vapor temperature case. The normal operating temperature on Venus was Tv3=850°C while the reservoir temperature was Tr3=460°C. The total power applied to the setup was 1200W to compensate for heat losses (heat losses were not measured but estimated, based on previous experience, as ~200W).

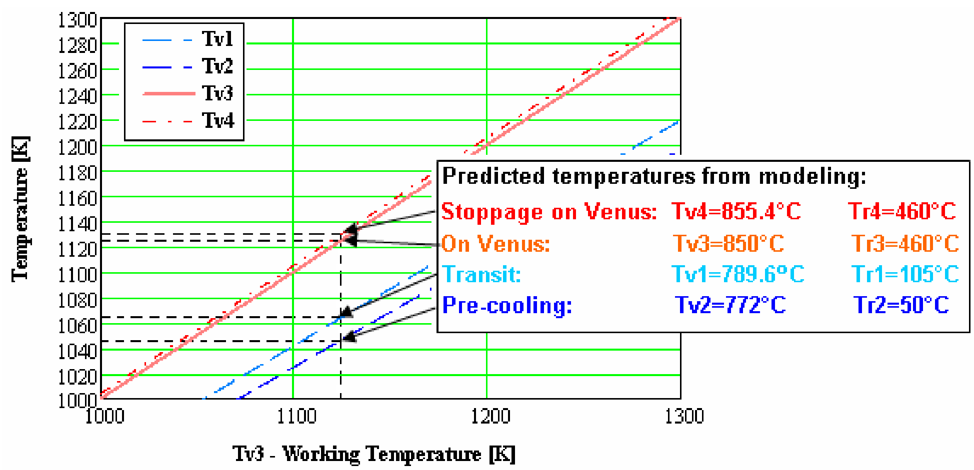


Figure 5. Modeling (predicted) parameters for Tv3=850°C nominal temperature (normal operation on Venus). The frame shows the predicted temperatures for vapor (in evaporator) and NCG (in reservoir) during the steady states of the 4 features that the VCHP handles.

Figure 5 shows the predicted temperatures of the VCHP for the actual geometry as a function of the nominal working point on Venus surface (Tv3). Once the operating temperature is chosen (Tv3), predicted temperatures for the other three cases (transit – Tv1, pre-cooling – Tv2, and stoppage on Venus – Tv4) can be calculated (as shown in the inset of the figure) for the actual case of Tv3=850°C with a reservoir temperature of Tr3=460°C. This temperature was reduced from the >1000°C temperature expected on Venus, to demonstrate the technology with an inexpensive, stainless steel system.

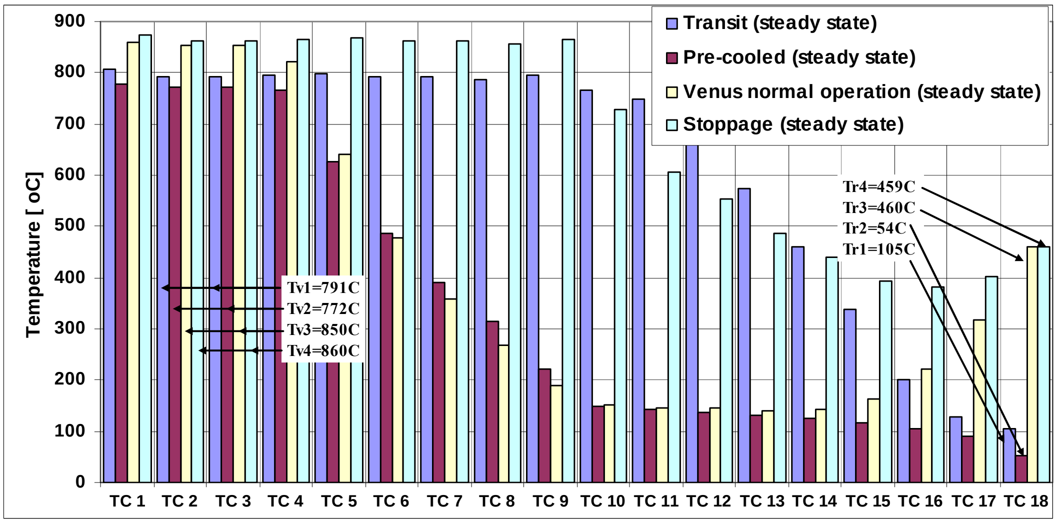


Figure 6. *Testing Results for Tv3=850°C:* steady state temperature distributions that correspond to the four features: transit, after pre-cooling, normal operation and stoppage. The experimentally measured temperatures are written on the plot for both evaporator and reservoir. Evaporator is represented by TCs 2 and 3, condenser by TCs 10-12 while the reservoir is TC 18.

Figure 6 shows the measured steady state temperatures corresponding to the four features for the 850°C (Tv3) operating temperature case. As shown in Table 2, good agreement was found between the predicted temperature values and the experimentally obtained ones for features 1, 2 and 4 (feature 3 is considered as reference or "input"). Also, the locations of the front in all four features fully validate the mathematical model based on the flat front theory.

Feature 1 (Transit): During transit, the objective is to have the heat rejected to the secondary condenser at a lower temperature than the operating temperature, while allowing the Stirling to be turned OFF (the compressed air cooling simulating the Stirling was shut OFF during this portion of the test). The transit steady-state temperature profile is the dark blue bars in Figure 6. The reservoir temperature is 105°C, and the heat pipe operating temperature is 791°C. The temperatures at TC10, 11 and 12 are high, indicating that the power is removed by the radiator. The radiator is oversized, so there is a drop in temperature from 10 to 12°C.

Feature 2 (Pre-Cooling): The objective during pre-cooling is to run the Stirling to drop the temperature of the entire system (including the GPHSs in the real system), prior to entry in Venus atmosphere. The Stirling is turned ON (compressed air cooling is turned ON), and the reservoir is colder than normal. This context allows the Stirling to be run at a lower temperature than normal. The pre-cooling steady-state temperature profile is the dark red bars in Figure 6. The reservoir temperature is 54°C, and the heat pipe operating temperature is 772°C. In Figure 6, the temperatures at TC2, TC3, and TC4 are fairly high, while the secondary condenser (radiator) temperature are low, so very little heat is removed by the radiator.

Feature 3 (Operation on Venus): Once the system lands on Venus, the NCG reservoir temperature will heat up to the ambient temperature increasing the operating temperature of the system before the second condenser operates. The yellow bars in Figure 6 shows the steady-state temperature profile during simulated operation on Venus; where the compressed air cooling is turned ON to simulate the Stirling system heat removal. The reservoir temperature is 460°C, and the heat pipe operating temperature is 850°C. During normal operation, the temperature TC1, TC2, and TC3 are high. The radiator temperature TC10, TC 11, and TC 12 are low, indicating that all of the heat is removed from the primary condenser (the simulated Stirling system).

Feature 4 (Stoppage on Venus): When the Stirling system is shut OFF on Venus, the temperature increases enough to uncover the secondary condenser (radiator), so that heat can still be removed from the GPHSs. The steady-state temperature profile for this case is the light blue bars in Figure 6. The reservoir temperature is 459°C, and the heat pipe operating temperature is 860°C. Increasing the temperature by about 10°C increases the sodium saturation pressure by enough to drive the NCG gas front back, activating the secondary radiator.

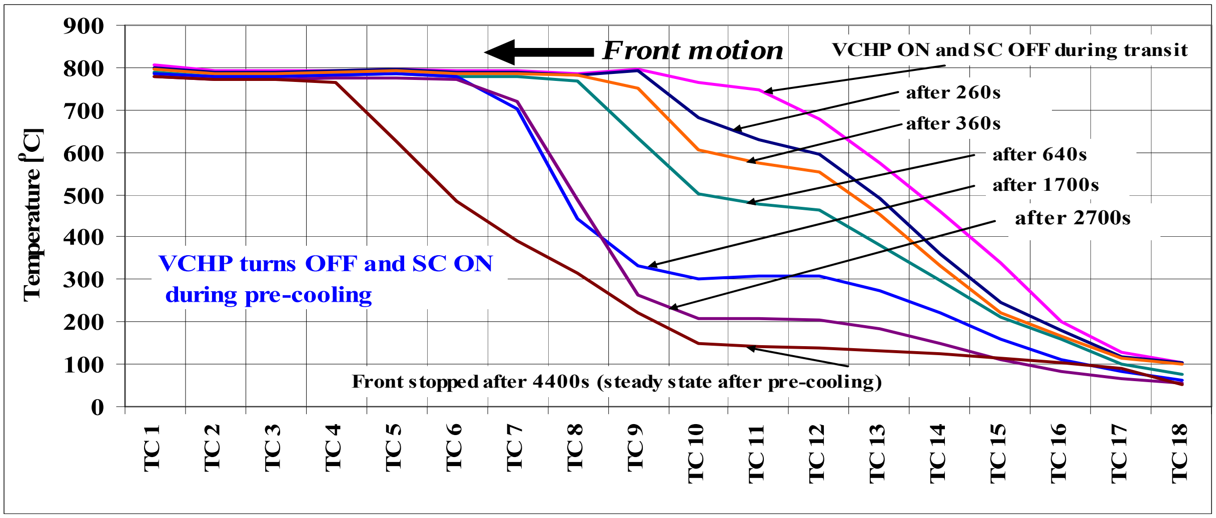


Figure 7. *Testing Results for Tv3=850°C:* transient temperature distributions going from transit to *pre-cooling*.

Figure 7 shows the transient temperature profiles going from steady state during ***transit*** (feature 1) and ending with the steady state that corresponds to "after pre-cooling" just before entry (feature 2). Stirling (cooling air) was started and the reservoir heating was reduced to drop reservoir temperature from 105°C to 54°C. This parameter configuration shuts OFF the secondary condenser and allows the simulated Stirling to operate at a lower temperature than during transit, when the Stirling was OFF and the secondary condenser was rejecting heat.

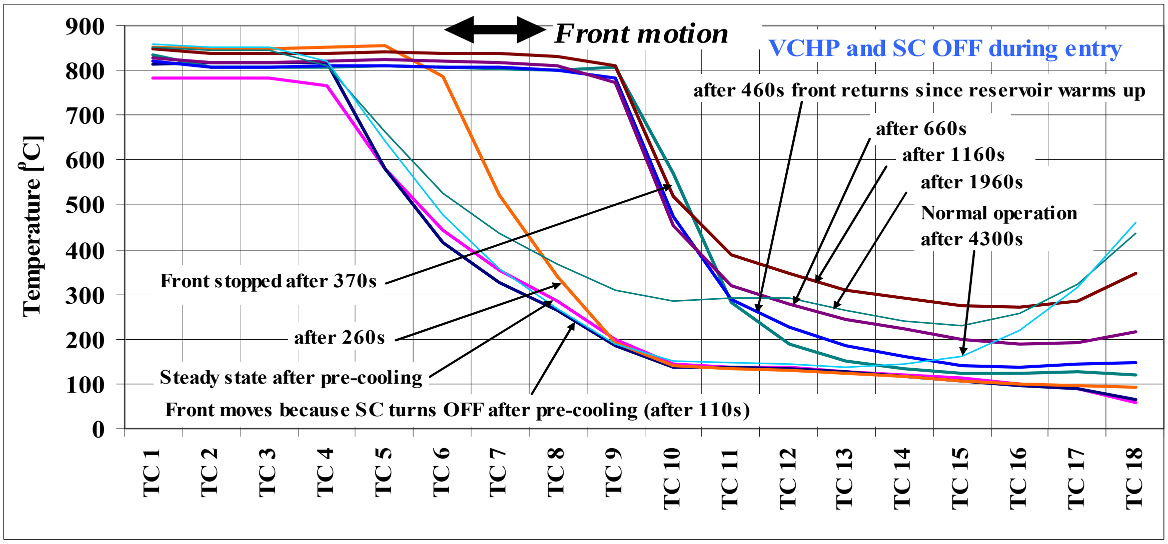


Figure 8. *Testing Results for Tv3=850°C:* transient temperature distributions going from pre-cooling to operation on Venus.

The transient temperature profiles switching from pre-cooling to normal (simulated) operation on Venus are shown in Figure 8. Note that while we state that this behavior occurs during entry, we have not tried to simulate the Venus landing conditions. We are only trying to show the transient behavior as the NCG reservoir temperature is increased. In Figure 8, the simulated Stirling is shut OFF during "re-entry". The front moves towards the right, activating the secondary radiator. At the same time, the power to the reservoir heaters is increased to simulate the increase in temperature as the system lands on Venus. The air cooling is turned back on, simulating the Stirling working on Venus. At a certain point (after 460s) the front moves back toward the evaporator because the reservoir starts to warm up on its way to 460°C and the Stirling convertor (SC) starts to work on Venus surface. This rather complex transient state finishes with the steady state that corresponds to normal operation in Venus environment (feature 3). The beginning of this steady state occurs ~ after 4300s.

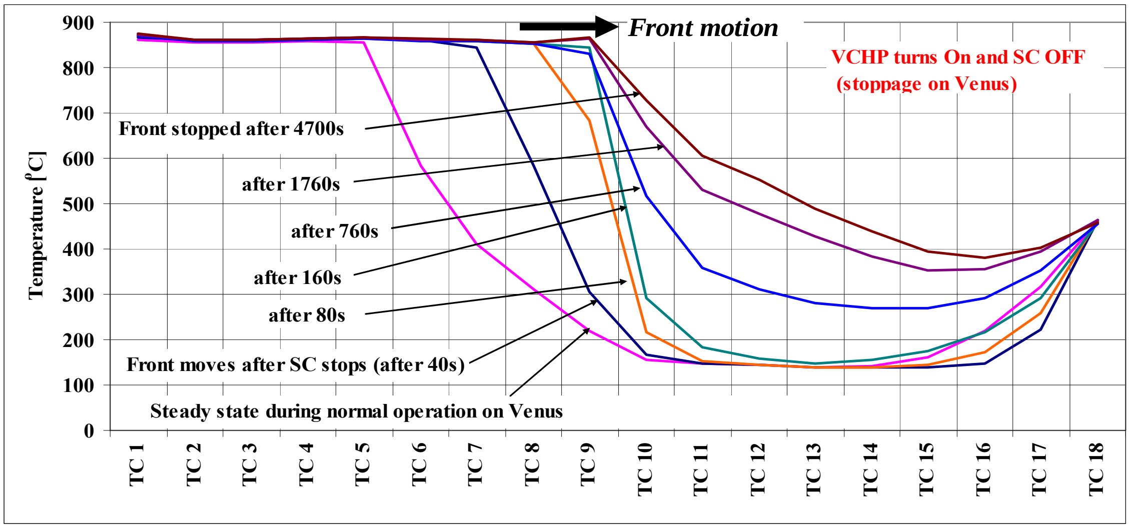


Figure 9. ***Testing Results for Tv3=850°C:*** **transient temperature distributions during** ***stoppage*** **on Venus.**

Figure 9 shows the transient temperature profiles when the Stirling stops on Venus. The vapor temperature increases, pushing the NCG gas front and uncovering the radiator (turning ON the VCHP). Steady state is reached for a vapor ΔT~10°C. Reservoir temperature is Tr4 ~ 460°C.

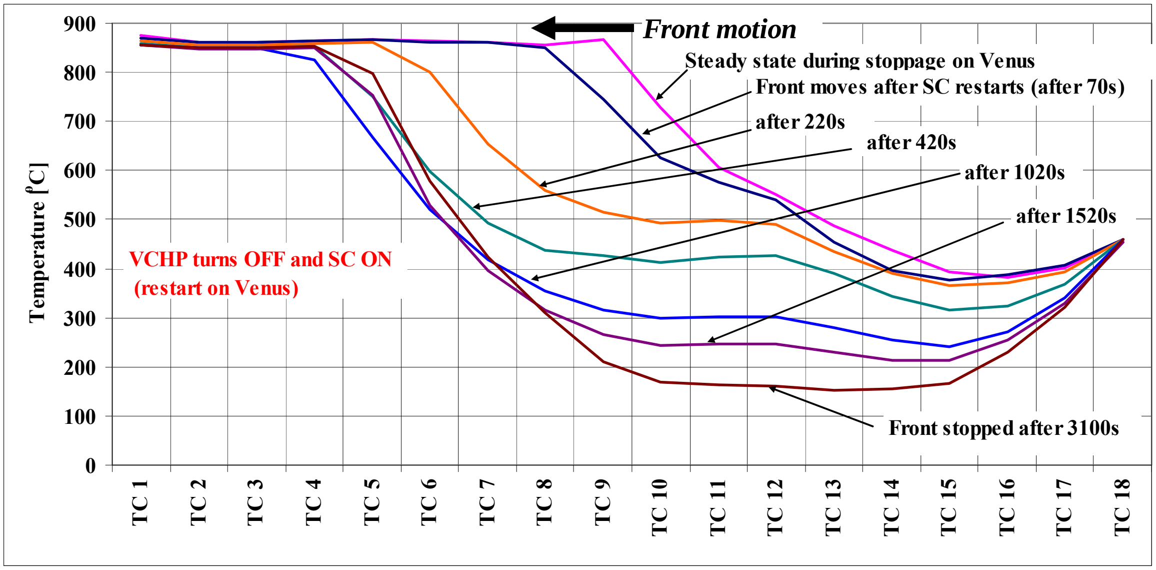


Figure 10. ***Testing Results for Tv3=850°C:*** **transient temperature distributions during SC** ***restart*** **on Venus.**

Figure 10 shows the transient behavior when the simulated Stirling restarts, while the VCHP turns OFF going from feature 4 (stopped on Venus) back to feature 3 (normal operation on Venus) The vapor temperature decreases and allows the front to retract to the evaporator where it eventually occupies the same steady state distribution (feature 3) as before stoppage. Reservoir temperature is Tr3 ~ 460°C.

Table 2 summarizes the experimental results for all three nominal temperatures, 780°C, 820°C and 850°C, where only steady state values (predicted and measured) are shown for the features tested during each case. Good agreement can be observed in all cases and features. Although the reservoir temperatures were controllable, some minor discrepancies can be observed between the predicted and obtained values. These differences resulted because of the reservoir's significant thermal inertia during cooling/heating when adjusting its temperature. However, based on these results, it is reasonable to consider that the analytical model is accurate. This fact is encouraging for further development and especially for experimental validation of the five-feature concept analytical model, when alternative (to Pu-238) isotopes, that have shorter half-life, are used.

Table 2. Summary of the experimental results – vapor and reservoir temperatures.

Case \ Feature		**Feature 1 Transit**		**Feature 2 Pre-Cooling**		**Feature 3 Venus Operation**		**Feature 4 Stoppage on Venus**	
Power = 1200W		***Tv1***	***Tr1***	***Tv2***	***Tr2***	***Tv3***	***Tr3***	***Tv4***	***Tr4***
780°C	**predicted**	745.7°C	100°C	730.6°C	50°C	780°C	305°C	784.7°C	305°C
	measured	747°C	98°C	N/A	N/A	780°C	325°C	787°C	322°C
820°C	**predicted**	769.3°C	100°C	753.6°C	50°C	820°C	400°C	825.1°C	400°C
	measured	774°C	98°C	752°C	55°C	820°C	398°C	828°C	398°C
850°C	**predicted**	789.6°C	105°C	772.6°C	50°C	850°C	460°C	855.4°C	460°C
	measured	791°C	105°C	772°C	54°C	850°C	460°C	860°C	459°C

VII. Five-Feaure Concept: Theoretical Demonstration

As shown in Table 3, the half-lives of alternate isotopes are much lower than the half-life of Pu-238. As discussed above, the HTTMS must be able to reject the excess heat generated before EOM. A particular case has been chosen: plutonium 238 (Pu-238) is entirely replaced by polonium 210 (Po-210), the isotope with the shortest half-life. Preliminary system calculations regarding the consequences determined by this replacement have been carried out, concentrating on both heat pipe performance limitations and VCHP fifth feature addition.

Table 3. Potential isotopes to work with the HTTMS.

Isotope	**Half-life**	**W/cm^3**	**W/g**
Pu-238	89.8 y	3.5	0.55
Po-210	138 d	75	141
Cm-242	163 d	75	120
Cm-244	18.4 y	26.4	2.74

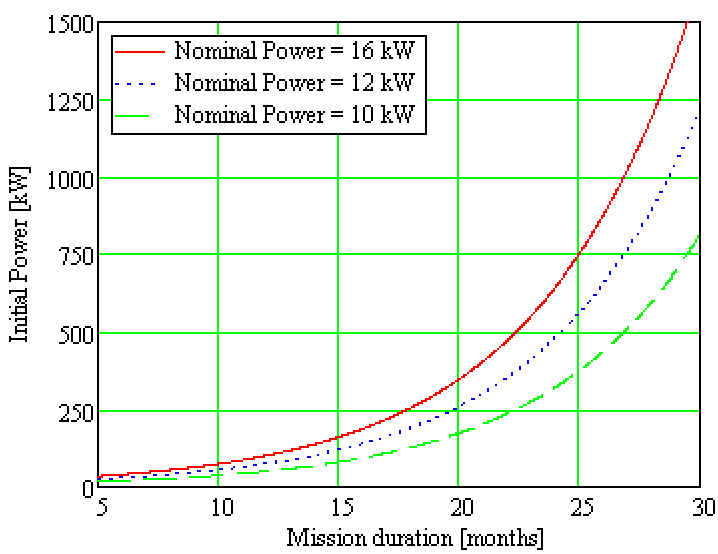


Figure 11. The necessary initial power of polonium (Po-210) based GPHS modules as a function on the mission duration and nominal power.

C. Five-Feature Concept: heat pipe performance limitations

The following isotope power decay formulation was used to estimate the mission initial power needs and the instantaneous power inventory on board along the mission:

$$P_{isotope}(t) = P_N \, 2^{\frac{D_{mission}-t}{HL}} \tag{1}$$

The plot in Figure 11 shows the required initial power (t=0 in eq. 1) when using Po-210 alone as a function of the mission duration and nominal power (10, 12 and 16 kW). For example, for a 18 month mission (including transit), the necessary initial power will be 256 kW. In the 22 VCHP configuration of the HTTMS, each VCHP will have to transport and reject ~ 12 kW.

Figure 12 shows several heat pipe performance limitations as a function of the inner diameter. These calculations have been performed for a 63.5 cm (25 inch) long heat pipe with sodium as the working fluid. The general geometrical configuration of this pipe corresponds to the one designed for the case where only Pu-238 is used (the 22 VCHP configuration). It can be seen in Figure 12 that the capillary limit is the lowest in space when the rejected power is the highest (BOM). So, for a 1.5 year mission, the 12 kW of initial power could be transported and rejected by a 3.81 cm (1.5 inch) I.D. VCHP. Note that these calculations are not optimized. Significant improvement can be obtained after a careful optimization of the pipe geometry and wick structure. If the general arrangement designed for the Pu-238 case (22 VCHPs) is maintained, the redundancy level could be maintained.

Flooding is another controlling limitation. However, for the chosen diameter, the magnitude is similar to the capillary limit.

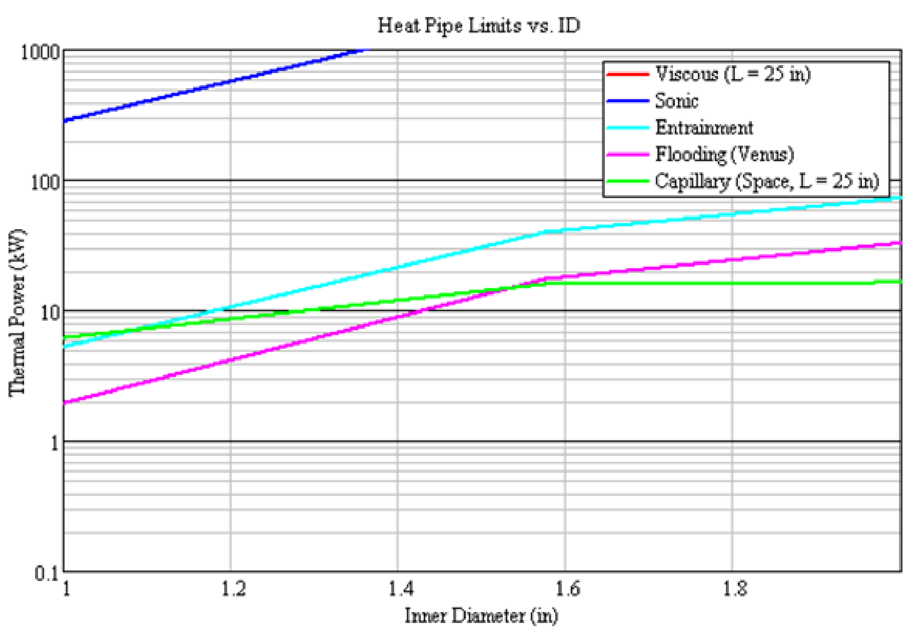


Figure 12. Sodium heat pipe limitations in space (no gravity) and Venus atmosphere (gravity aided) when its total length is fixed at 25".

The design of the five feature VCHP is strongly impacted by the time intervals during the mission (total time – $D_{mission}$, transit time, operation time) and by the P_N (nominal power). The following input information was assumed to design this preliminary VCHP:

Nominal Power, P_N = 16 kW
Mission Duration, $D_{mission}$ = 18 months
Transit Duration, $t_{transit}$ = 6 months

In these conditions, again, the initial power to be rejected by the HTTMS is 256 kW while the power per VCHP will be ~12kW (in a 22 VCHP configuration). The ID of the VCHP tubing will be 3.81 cm (1.5 inch). For a condenser length of 25.4 cm (10 inch) and diameter of 5.08 cm (2 inch) respectively, the initial heat flux will be ~51 W/cm^2, which is reasonable.

D. Five-Feature Concept: VCHP calculation

To accommodate the fifth feature, excess heat removal, the following analytical representations were added to the four feature VCHP model:

$$P_{rej}(t) = \begin{cases} \dfrac{P_N}{N_{VCHP}} 2^{\frac{D_{mission}-t}{HL}} \ \ if \ \ Stirling \ rests \\ \dfrac{P_N}{N_{VCHP}} 2^{\frac{D_{mission}-t}{HL}} - P_N \ \ if \ \ Stirling \ works \end{cases} \quad (2)$$

$$x_{front}(t) = \begin{cases} c1 \cdot P_{rej}(t) \ \ if \ \ Stirling \ rests \\ c2 \cdot (P_{rej}(t) - \dfrac{P_N}{N_{VCHP}}) \ \ if \ \ Stirling \ works \end{cases} \quad (3)$$

where:

- P_{rej} is the instantaneous power rejected by the VCHP radiator along the mission
- P_N is the nominal power needed for the refrigeration system
- N_{VCHP} is the number of VCHPs
- *IDc* is the internal diameter of the condenser
- x_{front} is the front location in the condenser with respect to the beginning of the condenser (vapor side).
- $c1 = \dfrac{Lc}{P_{rej}(t=0)}$ is a proportionality constant that includes rejection thermal resistance in space.
- $c2=1.1$ is also a proportionality constant that includes rejection thermal resistance on Venus and is chosen arbitrarily.
- *Lc* is the length of the condenser (the front can move only within this domain along the entire mission)

Based on the VCHP complete model and the particular data presented above, Figure 13, Figure 14 and Figure 15 below show the analytical representations for the rejected power, front location in the condenser and vapor temperature in the five feature VCHP, during the entire mission, for the following set of data:

- Isotope is Po-210 with *HL*=138 days
- P_N=16 kW
- $D_{mission}$=540 days
- *Lc*=10in
- *IDc*=2in (Internal diameter of the condenser)

Feature 2, pre-cooling, was not included in this analytical representation since it may not be suitable due to the higher power generation during re-entry. However, the concept, which is presented in Figure 2, includes this feature for completeness.

Figure 13 shows the power delivered by one VCHP as it decays during the entire mission assumed at 18 months. The red line shows only the power that reaches the second condenser and is rejected by the VCHP radiator while the dashed blue line show the total power inventory that is transported by the VCHP. The 10 day durations for each of the four stoppages were exaggerated just for representation. They are obviously much shorter. At EOM, all of the power is used to power the Stirling systems.

Figure 14 shows the behavior of the vapor – NCG front during the mission. The fifth feature, continuous and passive excess heat rejection, demands that the NCG front is always in the second condenser to reject the excess heat. The front location is measured as the distance between the front and the end of the second condenser that is nearest to the Stirling heater head. In fact, the front location shows the *active length of the condenser*. It can be observed that after 180 days of transit, the active length of the condenser suddenly becomes shorter. At this moment, the normal operation on Venus starts and 16 kW of power are directed to the heater head. The smaller condenser active length is a consequence of the passive thermal resistance adjustment to accommodate the new (lower) power rejected by the VCHP radiator at higher temperature.

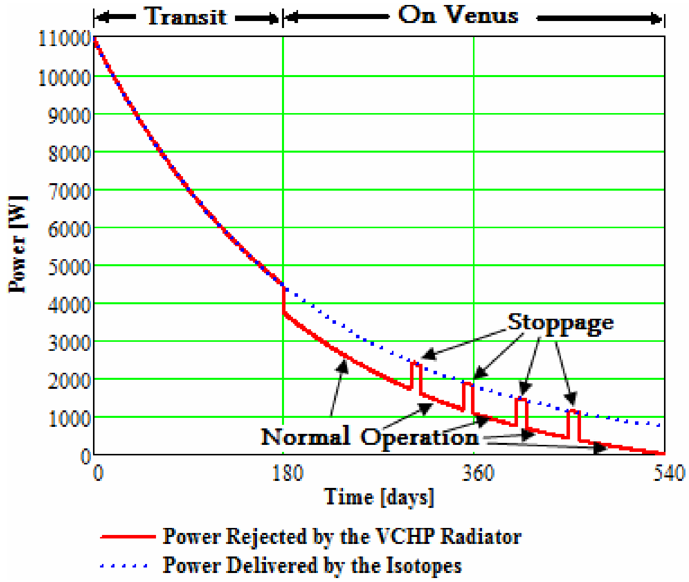
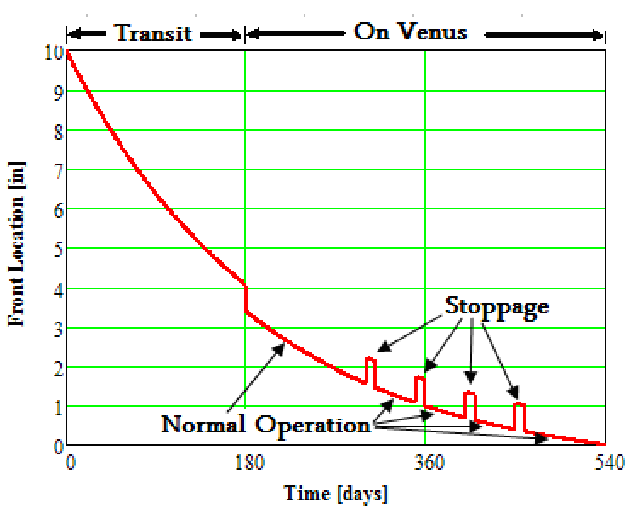


Figure 13. Power rejected by the five feature VCHP Radiator during the mission (however, pre-cooling was not included since it may not be suitable).



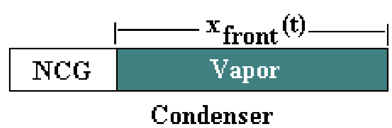


Figure 14. Front location in the five feature VCHP second condenser along the mission (pre-cooling was not included since it may not be suitable).

Figure 15 shows the vapor temperature within the VCHP during the entire mission. It can be observed that the continuous isotope power decay determines a slightly variable (decreasing) vapor temperature during the mission in each feature. In this particular example (Po-210) the 6 month period of transit determines a feature 1 vapor temperature decay of ~ 6º C while the 12 month period of operation on Venus surface (feature 3) determines a vapor temperature decay of ~ 6º C.

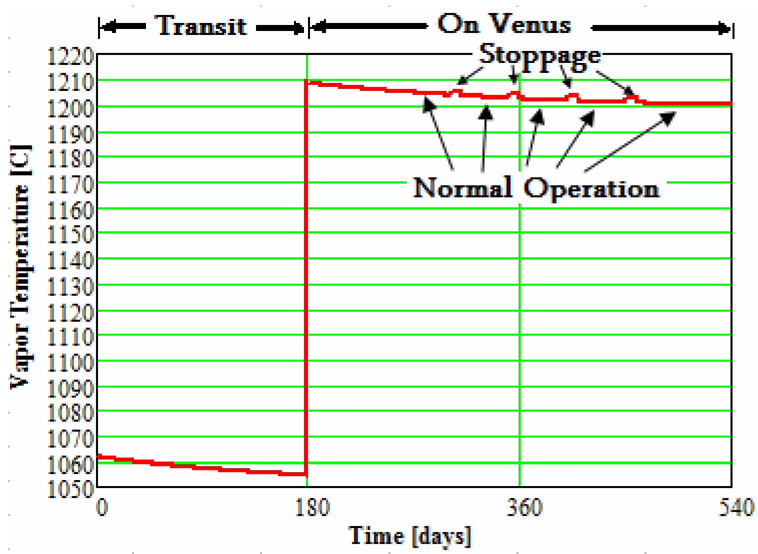


Figure 15. **Sodium vapor temperature in the five feature VCHP condenser along the mission (pre-cooling was not included since it may not be suitable).**

It has to be mentioned again that the two cases Pu-238 based and Po-210 based are the extreme cases in terms of complexity and difficultness in designing the HTTMS. While using only Pu-238 is the easiest case, using only Po-210 is the most unfavorable case. Hybrid configurations (in conjunction with Pu-238) or other alternative isotopes (Cm-242 or/and Cm-244) can be used (See Table3).

VIII. Conclusion

A sodium VCHP has been developed as part of the High Temperature Thermal Management System of the Long-Lived Venus Lander. In the four–feature configuration, this VCHP will allow the convertor to rest during transit, to pre-cool before Venus entry, to work under normal conditions on Venus and to execute multiple stops and restarts on Venus. The four-feature configuration, presented in this paper, was demonstrated both theoretically and experimentally. In the five-feature configuration, the VCHP will allow, in addition to the first four features, continuous excess heat removal when short-lived isotopes are used. This configuration was demonstrated only theoretically. The experimental demonstration (model validation) is the object of future work. Based on the four-feature configuration VCHP model, a reduced scale test setup was fabricated and tested for three nominal temperatures: 780°C, 820°C and 850°C. While the steady state results were summarized for all three cases, only the higher temperature case was presented in detail (transients) in this paper. Good agreement was observed between predicted and measured values for all cases and features. The minor discrepancies, however, were determined by the reservoir's significant thermal inertia during cooling/heating when adjusting its temperature. The overall conclusion is that the four-feature concept works and the mathematical model is accurate. This fact is encouraging for future development, and especially for the five-feature concept experimental demonstration, for the case when alternative isotopes with short half-life are used.

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References

Dyson, R.W., Schmitz, P.G., Penswick, L.B., and Bruder, G.A., "Long-Lived Venus Lander Conceptual Design: How To Keep It Cool," IECEC, August 5th, 2009, Denver, CO.