# Pressure Controlled Heat Pipe Solar Receiver for Oxygen Production from Lunar Regolith

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**The lunar soil contains approximately 43% oxygen as oxides, which could be extracted to provide oxygen for future Lunar bases. One method of extracting the oxygen is hydrogen reduction: the lunar regolith is heated using a solar concentrator to approximately 1050°C and exposed to hydrogen gas. Water is formed from the reaction and the oxygen is recovered by electrolysis of the water. To minimize mass, it is desirable for the solar concentrator to supply heat to more than one reactor. ACT is developing a thermal management system using Constant Conductance Heat Pipes (CCHPs) and Pressure Controlled Heat Pipes (PCHPs) solar receiver for this process. A PCHP is similar to a Variable Conductance Heat Pipe and permits control over heat pipe operation by varying the gas quantity or the volume of the gas reservoir. The PCHP solar receiver is designed to accept, isothermalize and transfer the solar thermal energy through CCHP's to multiple reactors for oxygen production. The final system will use sodium as the working fluid, with a Haynes 230 envelope material. This paper will report on the transient modeling and design and fabrication of a lower temperature system that was used to verify performance of the overall design.**

## Nomenclature

$A_{reactor}$ = area of reactor for heat loss due to radiation
$C_{p\_regolith}$ = regolith specific heat
$L_{VCHP\_Condenser}$ = maximum length of VCHP condenser
$L(t)$ = length of the condenser/evaporator at the SRHP-CCHP interface (front location)
$OD_{CCHP}$ = outer diameter of the CCHP
$t_{wall\_CCHP}$ = CCHP wall thickness
$OD_m$ = $OD_{CCHP} - t_{wall\_CCHP}$
$Q_{charging}$ = maximum amount of heat available for charging
$Q_{Loss}$ = power loss to the environment by the reactor (radiation)
$Q(t)$ = net instantaneous heat transfer rate into the regolith
$Q_{VCHP}$ = VCHP heat transfer
$t_{cycle}$ = regolith cycle time
$t_{charging}$ = regolith charging time for the first one-half of the cycle
$t_{front}$ = time when the NCG front sweeps the SRHP condenser and reaches the end
$t_{processing}$ = regolith processing time for the second one-half of the cycle
$t_{replenish}$ = regolith replenish time, when processed regolith is removed and new regolith is added
$Th_1$ = thermal resistance between SRHP and CCHP vapor
$Th_2$ = thermal resistance between the CCHP vapor and regolith
$T_R$ = regolith temperature
$T_{sink}$ = sink temperature

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$Tv_{CCHP}$ = CCHP vapor temperature
$Tv_{SRHP}$ = SRHP vapor temperature under normal operation
$V_{reactor}$ = volume of regolith
$\varepsilon_{reactor}$ = emissivity
$\rho_{regolith}$ = density of granular regolith
$\theta$ = thermal resistance per unit length at the SRHP-CCHP interface
$\sigma$ = Stefan-Boltzmann constant

## I. Introduction

The lunar soil contains approximately 43% oxygen that is contained within the oxides of the lunar soil. Extracting and processing this oxygen for consumption by astronauts or use in propulsion systems will significantly reduce the mass a spacecraft must transport from the Earth to the moon. Furthermore, lunar based oxygen production is an important step towards sustainable, Earth-independent habitation of the moon[1]. Realizing this goal would be invaluable for further exploration of the solar system[2].

For this reason, a number of potential processes have been examined for oxygen production, such as vacuum pyrolysis, ilmenite reduction by hydrogen and carbon, and magma electrolysis. Vacuum pyrolysis involves heating lunar regolith to high temperature, 2000-2600°C, which vaporizes the oxides and releases oxygen. Carbon reduction is a three step process and begins with heating the regolith to approximately 1600°C. Hot regolith is exposed to methane gas, which produces carbon monoxide and hydrogen. Temperatures are reduced in the second step to 200°C and the product gases of the first step combine to form methane and water. Water electrolysis comprises the third step, which results in oxygen[3]. Finally, hydrogen reduction operates at the lowest overall temperature range, 1000-1100°C, and is a two step process. Regolith is heated to temperature and exposed to hydrogen. The hydrogen reduces the oxides, resulting in liquid water. Like the carbon reduction process, oxygen is produced from electrolysis of this water[4]. A solar receiver comprised of sodium heat pipes operating in the 1000 to 1100°C temperature range is being developed for use with the hydrogen reduction process. The heat pipe solar receiver will accept, isothermalize and transfer the solar thermal energy to reactors for oxygen production using the available lunar soil. Direct illumination of the solar flux into a reactor core may generate non-uniform heating. Isothermalizing and transferring the thermal energy to the larger surface area increases the lunar regolith processing efficiency.

**Figure 1. NASA Oxygen Reactor Design[5].**

Early Phase I work focused on the design concept where a single solar concentrator supplied thermal energy to a single solar receiver and regolith reactor. The single reactor concept, shown in Figure 1[5], is being developed by NASA/JSC to demonstrate and understand regolith processing, such as the introduction of hydrogen into the regolith, auger performance, overall temperature cycles from material loading, processing to extract water and oxygen and material dump and re-fill. Future regolith processing is expected to change, where a single solar concentrator and heat receiver are used to supply power to process regolith over multiple reactors. In follow on Phase II development, this baseline foundation is being used to provide active thermal control using pressure controlled heat pipes.

## II. System Operational Requirement

A single one-half scale regolith processing plant is designed to produce up to 500 kg of oxygen per year[**]. For the half scale plant, the thermal power for the reactors is approximately 4.0 $kW_{th}$. 3.0kW of this amount is required to heat the regolith batch, and 1.0 $kW_{th}$ is required to make up for thermal losses of the batch to the environment, depending upon insulation design. To achieve near continuous regolith processing, dual processing reactors are being considered, where each will be operating out of phase. A projected operational scenario for the start up and operation of a multiple reactor system is as follows:

Step 1: Initially, 4kW of power would be put into the first reactor at startup. Step 2: The first reactor would reach 1050°C and 3kW is switched to heat up the second reactor. 1kW would be left in the first reactor for processing of the regolith. Step 3: At this time the second reactor would reach 1050°C and 2kW is switched back to

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[**] Simon, T., and Linne, D., Personal communication, April 28, 2008.

the first reactor giving a total of 3kW to first reactor and 1kW to the second reactor[††]. The spent regolith would need to be dumped and the reactor would be refilled during change-overs. The control of the thermal loading between multiple reactors, using a single solar receiver could be accomplished using pressure controlled heat pipes. It is also necessary to either defocus the concentrator, or dump the excess power during reactor filling.

Thermal input can be provided by either nuclear or solar sources. This effort is focusing on a single solar source for thermal input. The solar concentrator design and location on the lunar surface define the direction of the solar flux and the associated heat pipe receiver orientation. For operation in the Shackleton Crater on the South Pole, the solar flux will be incident from the lunar horizon and will be directed downward into the opening of the solar receiver. As a result, the heat pipe solar receiver is positioned vertically with respect to lunar gravity.

## III. Regolith Processing Thermal Management System Design

A Pressure-Controlled Heat Pipe (PCHP) is a variation on a Variable Conductance Heat Pipe (VCHP) that permits control over heat pipe operation by varying the gas quantity or the volume of the gas reservoir[6]. A PCHP is similar to a VCHP in that it contains a non-condensable gas. The principal difference is that the gas quantity can be varied, either with a bellows or piston, or a reservoir and pump. Varying the quantity of gas in the heat pipe will vary the length of the exposed condenser. There are two ways to achieve temperature control using a (PCHP): one is to modulate the amount of NCG in the reservoir; and, the other is to modulate the volume of the reservoir. The modulation of the amount of NCG in the reservoir is the conventional means of making a terrestrial based PCHP. In these applications, the NCG is added to or removed from the reservoir by means of a high pressure gas cylinder and a vacuum pump. The challenge for adapting this type of control system for use in space is to miniaturize the NCG supply tank and vacuum pump. More likely, a space based system would incorporate a small compressor and a small reservoir. The reservoir would be high pressure biased so that when NCG is required to be added to the PCHP, a simple solenoid valve would be activated and NCG would flow back into the PCHP. If NCG needs to be removed, the compressor would cycle on and pump NCG from the PCHP to the small reservoir.

Modulation of the reservoir volume is the other method of controlling the PCHP. In this concept, the NCG reservoir includes a bellows structure or a piston. A linear actuator is used to drive the position of the reservoir, thus modulating the volume of the reservoir. This concept is relatively simple in concept and requires only one active device. The challenge for this concept is to design and build a bellows type reservoir (mass and volume optimized), that can be varied with minimal power usage. For the thermal management system of this solar receiver application a PCHP could be used in a similar manner as shown in Figure 2. The system components would include:

1. A single solar receiver heat pipe (SRHP) with two PCHPs, one for each regolith processing reactor.
2. Two Constant Conductance Heat Pipes, one for each reactor.
3. VCHP extensions on the PCHPs, with bellows to vary the reservoir volumes.

The PCHP would be used to control the gas front location, and therefore control the power delivered to each reactor. The CCHP would be used to transfer the thermal load to the reactor from the variable PCHP. The change in the exposed length of the transport heat pipe would vary as the power was transferred. The VCHP extensions contain the non-condensable gas when the PCHP condenser is fully open. They also provide a method to dump waste heat, so that the concentrator can always deliver the full heat load to the PCHP.

## IV. Pressure Controlled Heat Pipe for Regolith Processing Modeling

A transient model was developed to describe the thermal behavior between both branches of the thermal management system during a multi-cycle time period. In the two reactor configuration of the lunar oxygen production facility, one reactor works to process oxygen from the lunar soil, while the other is replenished with regolith and warmed up for the next process cycle. The performance of each of the two reactors is shifted out of phase by one-half of the cycle, with one reactor heating up while the other reactor is producing oxygen. The total power available and supplied to the SRHP is approximately 4kW. The reactor producing oxygen needs approximately 1kW to compensate heat losses while the rest of the power is used to warm up the new regolith from the other reactor.

When the new regolith is introduced into the reactor, the heat transfer into the cold regolith must be scaled back, or throttled. Otherwise, the large temperature difference between the cold regolith (~ 600°C) and vapor of the

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[††] Oryshchyn, L., Personal communication, July 11, 2008.

CCHP would drive an unacceptably high heat transfer rate exceeding the 3kW available for charging. An important consequence would be that the SRHP vapor temperature and the associated CCHP would start to decrease, so that the temperature of the processing reactor would drop too low. Regulation of the thermal power can be achieved by adjusting the vapor–NCG interface location to set the CCHP evaporator / SRHP condenser length. During the first stage of the warm-up period, the reactor can accept the full 3kW of heat from the system. In this case the vapor front is located near the tip of the CCHP condenser, designated "A" in Figure 3. In the second stage, the front reaches the end of the condenser, "B", and the entire condenser length becomes exposed. The temperature difference that now is reduced cannot drive the entire amount of available power (3kW) into the regolith. The vapor-NCG front moves into the VCHP extension, "C", and the excess power is now rejected into the environment by the VCHP extension.

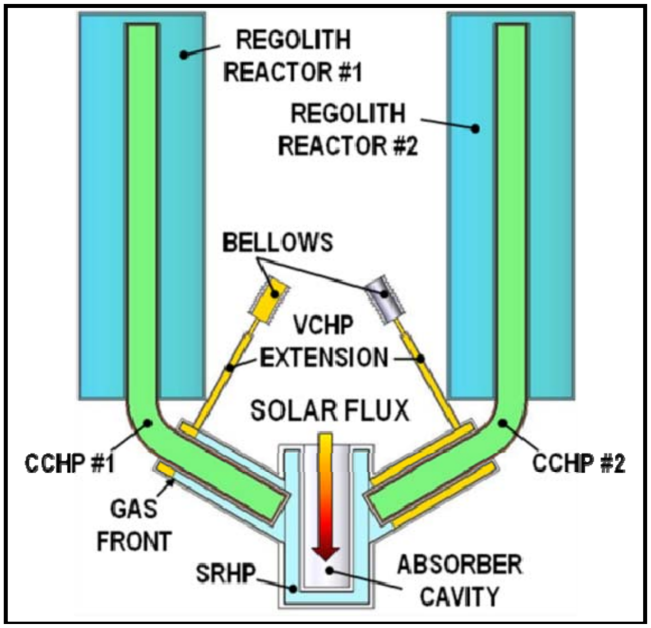

**Figure 2. Regolith processing thermal management system using Pressure Controlled Heat Pipes and Constant Conductance Heat Pipes. Bellows are used to vary the reservoir volume and adjust the exposed evaporator length of the CCHP, thereby regulating the thermal power delivered to each reactor.**

The transient model for the SRHP-CCHP-VCHP-Regolith heat transfer (Figure 3) was developed to evaluate the following characteristics:

- Time necessary for the new regolith to reach the nominal temperature.
- Power requirements during this transient period.
- A control scheme for the front motion during the transient period to optimize the process (to obtain the shortest heating time using the maximum available power).

The assumptions used in this transient model are as follows:

- 4kW maximum power to be transferred from SRHP to the CCHPs.
- Front location changes to maintain 3kW driven into the regolith during the first part of charging.
- Front moves into the VCHP to remove the excess heat during the second part of charging.
- SRHP vapor temperature is kept constant at 1050°C.
- CCHP vapor temperature changes.
- Regolith initial temp is 600°C.
- Regolith temperature is considered uniform at all times (stirred).
- All thermal resistances are considered.
- SRHP-to-CCHP and CCHP-to-Regolith heat transfer rates are equal at all the times.
- Thermal resistance at the regolith – CCHP condenser interface is very small.
- All thermal masses are neglected except the regolith.
- Regolith properties are not temperature dependent.

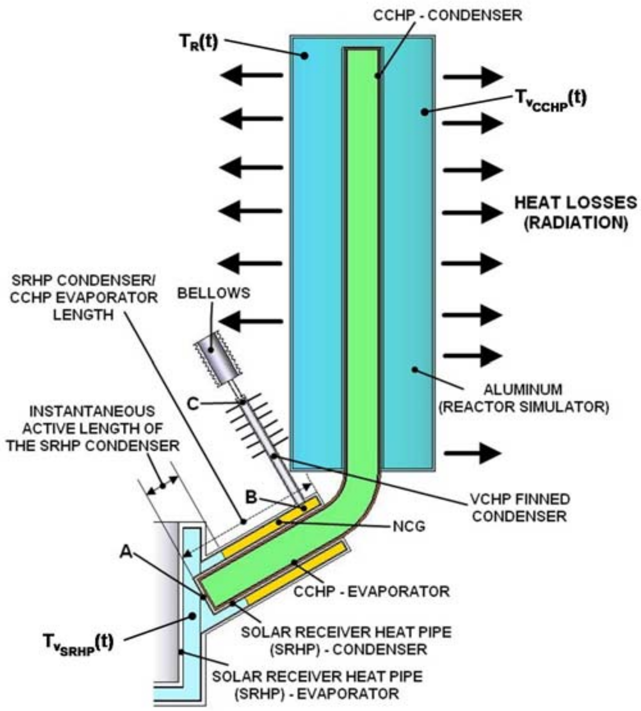

**Figure 3. One-half of the thermal management system of the lunar regolith oxygen production facility.**

The transient model was built considering the following time intervals within one cycle: $t_{charging}$, $t_{front}$, $t_{processing}$, $t_{replenish}$. The mathematical relationships among these time intervals are:

$$t_{charging} = t_{processing} + t_{replenish} = \frac{t_{cycle}}{2} \tag{1}$$

$$t_{front} \subset t_{charging} \tag{2}$$

The governing equations for the transient model of the entire thermal management system are detailed below. For one reactor branch these equations can be used in their current form while the other reactor branch is solved by using $t \to t + t_{cycle}/2$. The regolith reactor energy balance is described by the following differential equation:

$$\frac{dT_R}{dt} = \frac{Q(t) - Q_{\ Loss}(t)}{V_{reactor} \cdot \rho_{regolith} \cdot C_{p\_regolith}} \tag{3}$$

Assuming that the instantaneous power going into the CCHP is equal to the power leaving the CCHP, the instantaneous power transferred from the SRHP vapor to the regolith reactor can be described by:

$$Q(t) = \left| \begin{array}{l} \quad Q_{charging}\ , if\ t \in \left(0, t_{front}\right) \\ \dfrac{(Tv_{SRHP} - T_R)}{\left(Th_1\left(L(T_R)\right) + Th_2\right)}\ if\ t \in \left(t_{front}, t_{cycle}\right) \end{array} \right. \tag{4}$$

Again, assuming that heat losses from the regolith reactor consist only of radiation, they can by written as:

$$Q_{Loss}(t) = A_{reactor} \cdot \varepsilon_{reactor}.\sigma \cdot (T_R(t)^4 - T_{sink}^4) \tag{5}$$

Based on the assumption made above, for equation (4), the CCHP vapor temperature can be calculated with:

$$Tv_{CCHP}(t) = \frac{(Tv_{SHRP} \cdot Th_2) + \left(T_R(t) \cdot Th_1(t)\right)}{Th_1(t) + Th_2} \tag{6}$$

At this point, the time dependent heat rejected by the VCHP, the active length of the VCHP and the active length of the SRHP condenser/CCHP evaporator can be described by equations 7, 8 and 9 as follows:

$$Q_{VCHP}(t) = \left| \begin{array}{l} 0 \; if \; t \in \left(0, t_{front}\right) \cup \left(t_{charging}, t_{cycle}\right) \\ Q_{charging} - \left(\dfrac{Tv_{CCHP}(t) - T_R(t)}{Th_2}\right) \qquad if \; t \in \left(t_{front}, t_{processing}\right) \\ Q_{charging} \; if \; t \in \left(t_{processing}, t_{charging}\right) \end{array} \right. \tag{7}$$

$$L_{VCHP\_Front}(t) = Heat_{VCHP}(t) \cdot \left(\frac{L_{VCHP\_Condenser}}{Q_{charging}}\right) \tag{8}$$

$$L(t) = \left| \begin{array}{c} \dfrac{\left(\theta \cdot Q(t)\right)}{(Tv_{SRHP} - T_R(t) - Q(t) \cdot Th_2) \cdot OD_m} - \dfrac{OD_m}{4} \; if \; t \in \left(0, t_{cycle} - t_{replenish}\right) \\ 0 \; if \; t \in \left(t_{cycle} - t_{replenish}, t_{cycle}\right) \end{array} \right. \tag{9}$$

It is assumed that before the beginning of one cycle, the front is located at the tip of the CCHP evaporator interrupting the power supply from the SRHP to the CCHP with cold regolith. This quick motion of the front was assumed to have been carried at the end of the previous cycle when the regolith replenishing started. When the cycle starts, the front is quickly located at the initial location (~ 0.25 inches from point A at t=0 as shown in Figure 3).

The boundary conditions for the analysis follow. The analysis was carried out using a specific heat and density of 750 J/kg-K[7] and 1,700 kg/m$^3$ [8], respectively. The regolith volume was 0.015m$^3$ to nearly match the ROxygen reactor dimensions (see Fig. 1). Total power available was ~ 4kW while the available charging power was 3kW. Heat loss by radiation was assumed, with an emissivity set at 0.016 to match the heat losses from the insulated reactor (~1000W) and simulate the entire thermal resistance between the regolith and the environment. The SRHP vapor temperature and the environment sink temperature were 1323K and 100K, respectively. The replenishing time, $t_{replenish}$, was arbitrarily chosen as 300s. Evaporation and condensation heat transfer coefficients were assumed as 10,000W/m$^2$-K while regolith thermal conductivity was 1,000W/m K (stirred)[7]. The VCHP condenser length was 8.5inches. Cooling conditions at this interface were not set since they did not influence the thermal behavior of the system.

One solution output from the model is represented in Figure 4 through 6, where temperature, powers and front locations of the thermal management system are represented for both reactors simultaneously, but on different plots for clarity.

Both regolith and CCHP vapor temperatures are shown in Figure 4. The two temperatures increase at the start of the cycle, approaching steady state after approximately 4736s that represents the charging time, $t_{charging}$. The charging time sets the duration of "On" cycle which is $t_{cycle} = 2 \cdot t_{charging} = 9473s$ . During the first part of the charging time the temperature difference between CCHP vapor and regolith is constant because of the constant power that is continuously applied ($Q_{charging} = 3000W$) through a constant thermal resistance, $Th_2$. When the front reaches the end of the condenser, after $t_{front} = 2950s$, the temperature difference decreases and the power starts to decrease. The excess power is then rejected by the VCHP as the gas front moves up inside the VCHP.

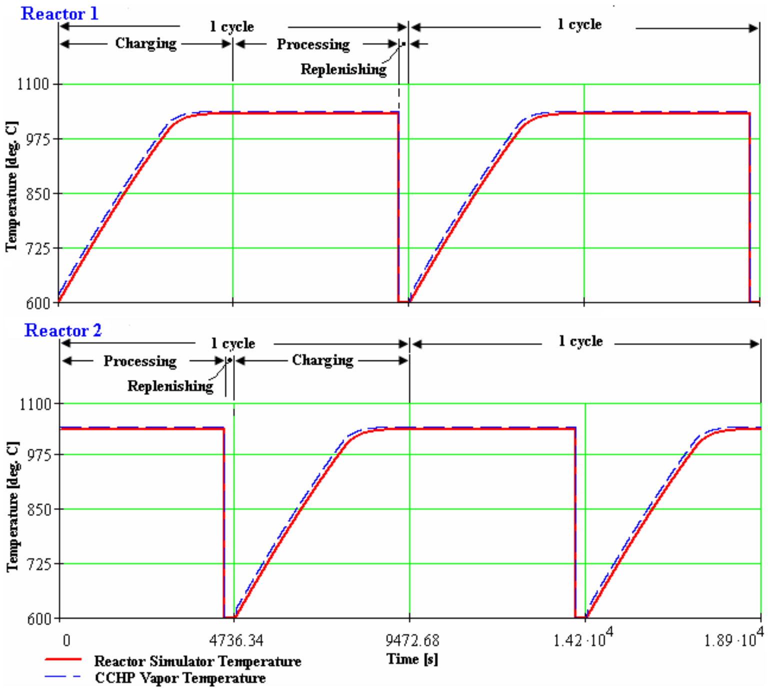

**Figure 4. Transient regolith and CCHP vapor temperatures for the two reactors during two cycles.**

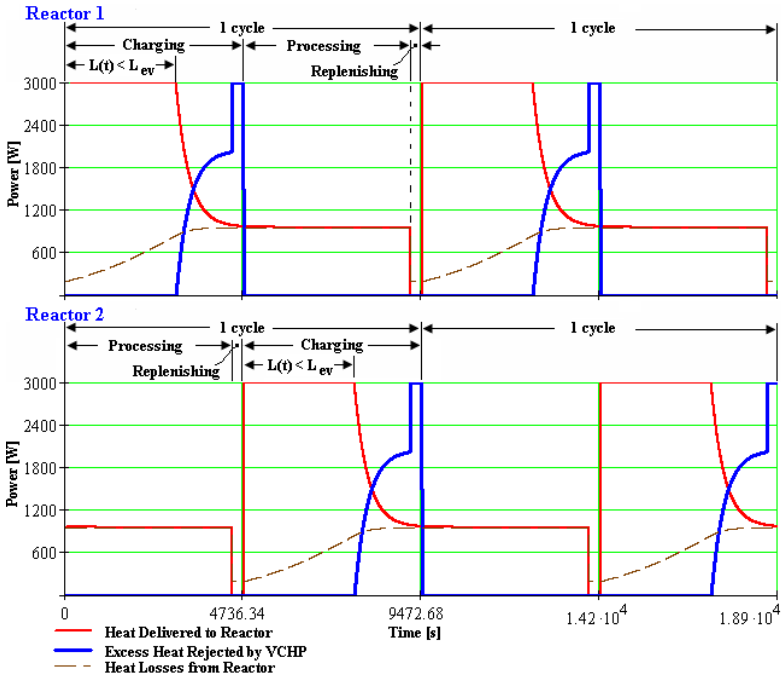

**Figure 5. Heat flow rate (Q) from SRHP to regolith for each reactor.**

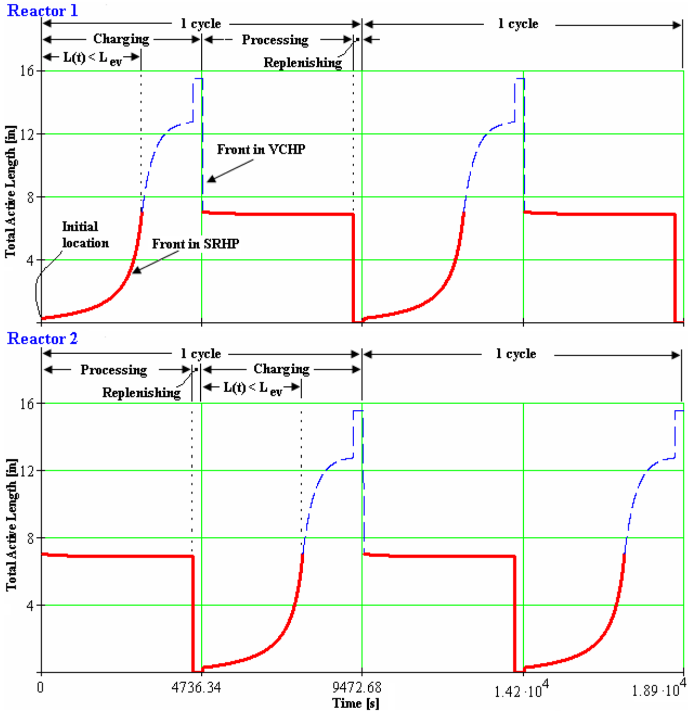

**Figure 6. Transient active length (L) of condenser (SRHP) / evaporator (CCHP) to maintain 4kW, for each reactor.**

At the end of the processing interval the regolith is replenished. The new regolith is assumed to be preheated at 600°C. In the beginning of the replenishing time interval, the front is quickly located inside the SRHP, "A" and consequently the delivered power to regolith becomes zero. This action increases the excess heat on the other branch and is removed also by the VCHP (see the step wise increases on the VCHP rejected power and front location in Figure 5 and Figure 6). In Figure 6, the front displacement along the SRHP condenser was concatenated with the front displacement along the VCHP condenser for clarity. In other words, the plot represents the overall location of the front with respect to the beginning of the SRHP condenser.

## V. Experimental Testing

The design and control scheme for the SRHP lunar regolith processing system are complex. As a result, a lower cost, lower temperature system was designed and fabricated from Monel, using water as the working fluid to demonstrate the operating system without the complexity of using an alkali metal working fluid. The advantages of the water/Monel system include lower cost, ease of fabrication, and the ability to make changes to the system and recharge the heat pipe. The small scale demonstration system is similar to the design of the full scale system; however, it is scaled down, carrying roughly one-tenth of the full power. The Monel and water demonstration system can be seen in Figure 7. The components of the system include:

- Solar receiver heat pipe (SRHP)
- Constant conductance heat pipe (CCHP)
- Heater block
- Aluminum cooling block (to simulate the cold regolith)
- VCHP extension (with attached fins to dissipate the heat through forced conduction)
- Piston
- Stepper motor

The operating temperatures for the system ranged from a minimum of 20°C to a maximum of 120°C with an operating power of approximately 300W. The small-scale demonstration consists of one-half of the full scale system; one SRHP and one CCHP. The full system will consist of two symmetric sides, but the demonstration unit was only built as a one-sided system to simplify for initial testing. The vertical, solar flux receiving portion of the solar receiver heat pipe was removed from the small scale demonstration to also aid in simplifying the system. A heater block was used to simulate the solar flux the real system would receive from the solar concentrator. Cartridge heaters inserted into the heater block provided the thermal power for the system. An aluminum cooling block was used to simulate the cold regolith that will be used in the real system. Liquid nitrogen was used as the mechanism of cooling in the aluminum block. Fins were added to the VCHP extension and a fan was used to generate forced convection to dissipate excessive thermal power. A stepper motor and a piston were used to adjust the NCG front location.

The dimensions for the Monel system can be seen in Table 1 for the SRHP, VCHP and CCHP. The CCHP is fabricated from a 1-1/2 in, schedule 40 Monel pipe with a 60 degree bend in the adiabatic section. The SRHP is fabricated from a 1-1/4 in, schedule 10 Monel pipe with a 30 degree bend in the adiabatic section. A Monel screen mesh was used as the wick structure for the demonstration unit.

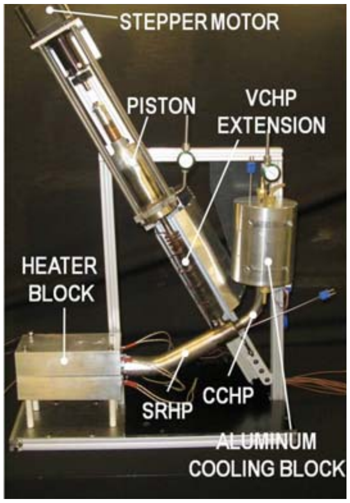

**Figure 7. Monel and Water Single Sided System.**

**Table 1. Demonstration Thermal Management System Dimensions.**

| Monel/Water SRHP and VCHP Dimensions | | Monel/Water CCHP Dimensions | |
|---|---|---|---|
| **Parameter** | **Value** | **Parameter** | **Value** |
| Outer Diameter | 1.660 in (4.216 cm) | Outer Diameter | 0.840 in (0.422 cm) |
| Wall Thickness | 0.109 in (0.277 cm) | Wall Thickness | 0.109 in (0.277 cm) |
| Inner Diameter | 1.442 in (3.663 cm) | Inner Diameter | 0.674 in (1.712 cm) |
| Evaporator Length | 4 in (10.16 cm) | Evaporator Length | 3 in (7.62 cm) |
| Side Arm Length | 4 in (10.16 cm) | Condenser Length | 6 in (15.24 cm) |
| Side Arm Bend Angle | 30 deg | Adiabatic Bend Radius | 3 in (7.62 cm) |
| VCHP Extension OD | 0.540 in (1.372 cm) | Adiabatic Bend Angle | 60 deg |
| VCHP Extension Length | 10 in (25.4 cm) | Adiabatic Length | 3.142 in (7.978 cm) |
| Fin OD | 1.29 in (3.277 cm) | Envelope Type | Monel |
| Fin Length | 8 in (20.32 cm) | Wick Type | 150 Mesh Monel Screen |
| Envelope Type | Monel | Number of Wraps | 3 |
| Wick Type | 150 Mesh Monel Screen | | |
| Number of Wraps | 3 | | |
| NCG Volume | 3.237 in$^3$ (53.044 cm$^3$) | | |
| Side Arm Gap | 0.301 in (0.765 cm) | | |

The Monel and water system was equipped with a total of 35 thermocouples (TCs): 25 spot welded to the outer surface of the heat pipes, 3 vapor well TC's in the SHRP evaporator and condenser, and CCHP condenser, and spring loaded TC's in the heater and condenser blocks. The number of TC's track the NCG front in incremental levels. A small change in piston location could result in a much larger change in the location of the NCG front and it was important to have a high resolution of TCs in the SRHP condenser to be able to track these changes.

The test procedure for the demonstration unit is described next. For the full-scale high temperature system the processing temperature for the regolith will be 1050°C; however, for the small scale demonstration unit the actual value is arbitrary so it was chosen as 120°C. After the regolith, or in this case the aluminum block representing the lunar regolith, has reached the processing temperature, the power will be transferred from one side of the system to the other to aid in "heat up" of the second regolith reactor. For the demonstration unit the transfer of power from one side to the next was represented by simply decreasing the power being provided to the system from 300W to 50W. The regolith reactor will process the lunar regolith for approximately 1 hour in the full-scale system. For the demonstration unit, the time to process was arbitrary and was chosen as anywhere from 30 to 45 minutes. After processing, the lunar regolith is dumped and new lunar regolith is added. This was represented in the demonstration unit by turning on the liquid nitrogen being provided to the aluminum block with a set point of 20°C. Once the aluminum block reached the set point, the LN was turned off signaling the start of another “heat up” process. The piston and the associated gas front position were controlled using the SRHP evaporator temperature. Changes in the CCHP condenser temperature, simulating regolith load, process and replenish, result in changes in the evaporator temperature and the associated NCG gas front.

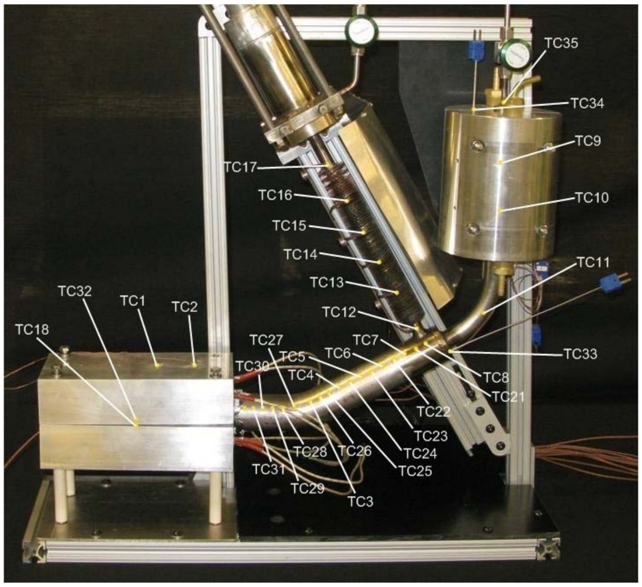

**Figure 8. Monel and Water Demonstration Unit TC Locations.**

The results from testing can be seen in Figures 9 and 10. Figure 9 shows the temperature and power as a function of time during 3 cycles. Five TC’s were chosen for these figures for clarity in the graph. The temperatures plotted were the SRHP evaporator vapor temperature, the SRHP condenser vapor temperature, the CCHP condenser vapor temperature, the SRHP condenser temperature at the inlet of the VCHP extension (surface mount) and the SRHP condenser temperature at approximately the middle of the SRHP condenser (surface mount).

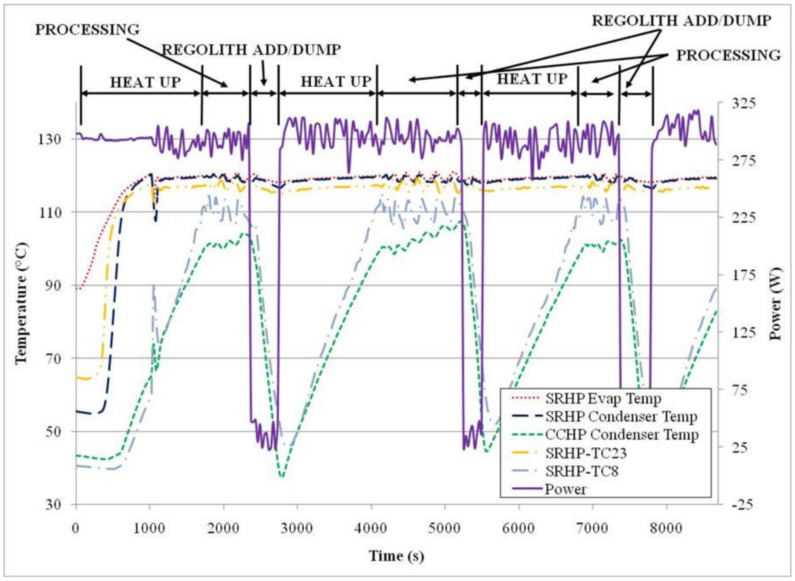

**Figure 9. Power and Temperature Plots during Cycling Testing of Monel and Water Demonstration System.**

The control scheme maintains an approximate evaporator temperature of 120°C regardless of the amount of power the system is being provided. The SRHP condenser temperature is maintained at approximately the same temperature as the SRHP evaporator. The temperature of TC 23 stays at approximately the same temperature as the SRHP evaporator and condenser. This shows that the NCG front is not located at these particular points. TC 8, located at the inlet of the VCHP extension, fluctuates from approximately 40 to 110°C during operation. This shows that the NCG front is indeed blanketing the CCHP evaporator at the low temperature points, preventing the thermal load from transferring to the CCHP. This is also evident by the fluctuation in the CCHP condenser from approximately 40 to 100°C. For the given operating conditions, it would be more ideal for the CCHP condenser temperature to range from 20 to 120°C; however this plot shows that the PCHP design is effectively shutting off power from being transferred to the CCHP and the regolith block while still maintain the 120°C temperature in the evaporator regardless of the amount of power being provided or the sink conditions. Further modifications will need to be made to the operating program for the piston to improve the temperature range experienced in the CCHP condenser.

Figure 10 shows the NCG front location during operation of the two extremes; CCHP fully on and CCHP fully off. For the CCHP fully on scenario the NCG front should be fully retracted into the piston exposing the entire length of the CCHP evaporator to ensure maximum surface area for heat transfer to the CCHP. For the CCHP fully off scenario the NCG front should be fully extended into the SRHP condenser, blocking off the entire CCHP evaporator from receiving any thermal energy. The plot shows that during CCHP on operation the temperature distribution across all the TCs is fairly isothermal. The reason the temperatures in the VCHP extension are low is due to the fan being operational and blowing across the VCHP extension. This shows that the NCG front was located either somewhere in the VCHP extension or entirely in the piston. For the CCHP fully on scenario, the NCG front should be fully retracted into the piston, allowing thermal energy to transfer from the SRHP to the CCHP. The plot shows the temperatures gradually decrease starting from roughly TC 21. This gradual decrease in temperature indicates that the NCG front is present in these locations and is blocking off the CCHP evaporator from receiving thermal energy.

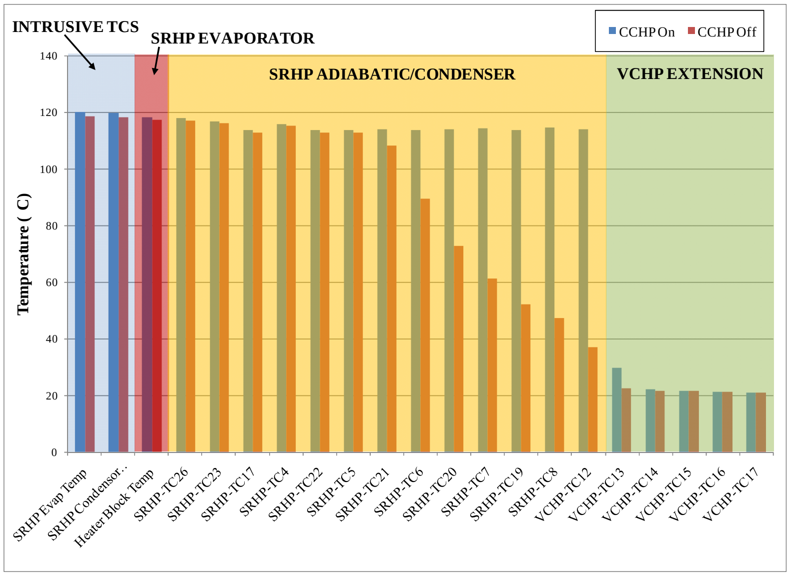

**Figure 10. NCG Front Location for CCHP on and CCHP off Conditions for Monel and Water Demonstration System.**

## VI. Conclusion

Methods to control the thermal loading from a single solar source to multiple lunar regolith oxygen processing reactors are being investigated using a thermal management system including Pressure Controlled Heat Pipes and Constant Conductance Heat Pipes. Thermal energy is introduced into the aperture of a Haynes 230/sodium heat pipe operating at 1050ºC. This temperature must be maintained to efficiently process oxygen from lunar regolith using the hydrogen reduction process. The sodium heat pipe is a PCHP with an integral CCHP. The amount of thermal energy is adjusted between multiple reactors by varying the volume of non-condensable gas (NCG) in the PCHP using a bellows or piston and stepper motor. This paper describes the PCHP/CCHP thermal management system. Transient thermal modeling is provided between two regolith reactors that are operating near out-of-phase to generate a near constant supply of oxygen. The model predicts the regolith charging, processing and replenishing temperatures, heat transfer and NCG front location. A low temperature smaller scale system has been designed and fabricated using a Monel/water heat pipe system to understand performance characteristics and NCG control prior to using alkali metals. Preliminary testing indicates that the NCG can be controlled to effectively throttle the thermal load to the CCHP and the lunar regolith. The next step is to build the other half of the low temperature simulator, to demonstrate power shuttling back and forth between the two regolith simulators.

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