Pressure Controlled Heat Pipe Solar Receiver for Regolith Oxygen Production with Multiple Reactors

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Oxygen from lunar regolith can be extracted to provide breathable oxygen for consumption by astronauts during long term stays on the Moon. The regolith is heated using concentrated solar energy to 1050°C, and then hydrogen is introduced that reacts with the regolith, extracting oxygen in the form of water vapor. After several hours, the regolith is dumped, and fresh regolith is added. To minimize mass, it is desirable to supply thermal energy to multiple reactors with a single concentrator. Pressure Controlled Heat Pipes (PCHPs) can be used to transfer heat to the multiple reactors from a single heat source. During operation, one reactor is producing hydrogen at low solar power, while the other reactor is warming up a fresh batch of regolith. The PCHPs switch power between the two reactors as required. A high-temperature, demonstration system was designed, fabricated and tested using two PCHPs and two Constant Conductance Heat Pipes (CCHPs) to supply heat to two reactors. The system was fabricated with Haynes 230 as the envelope, sodium as the working fluid, and argon as the non-condensable gas. Tests demonstrated the use of PCHPs to switch power between two reactors as required, as well as provide a means to reject excess power.

Nomenclature

CCHP	=	Constant Conductance Heat Pipe
NCG	=	Non-Condensable Gas
PCHP	=	Pressure Controlled Heat Pipe
SRHP	=	Solar Receiver Heat Pipe
VCHP	=	Variable Conductance Heat Pipe

I. Introduction

The lunar soil contains approximately 43% oxygen 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. A solar receiver comprised of sodium heat pipes operating in the 1000 to 1100°C temperature range was 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.

Production of oxygen from regolith is a batch process. A single one-half scale regolith processing plant is designed to produce up to 500 kg of oxygen per year[3]. Fresh regolith is added to a reactor, then heated up to 1050°C

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using roughly 4 kW of solar power. After the reactor is at 1050°C, hydrogen flows though the reactor, and reacts with the oxygen in the lunar regolith to produce water. The water is then electrolyzed to produce oxygen, and recycle the hydrogen into the process. During the oxygen production process, the reactor requires only about 1 kW of solar power to maintain the temperature. The spent regolith is dumped after the oxygen is extracted, and a new, cold batch of regolith is loaded into the reactor.

The mass of the overall system can be minimized if one solar concentrator supplies a constant rate of power to two (or more) reactors, with the power switched from one reactor to the other as fresh batches of regolith are added. A solar receiver with two or more reactors must do the following:

- Accept non-uniform flux from the solar concentrators
- Provide uniform heat flux to the vessels with lunar regolith
- Switch Power from one reactor to another as required
- Prevent the temperature from dropping when cold regolith is added
- Dump excess heat as required

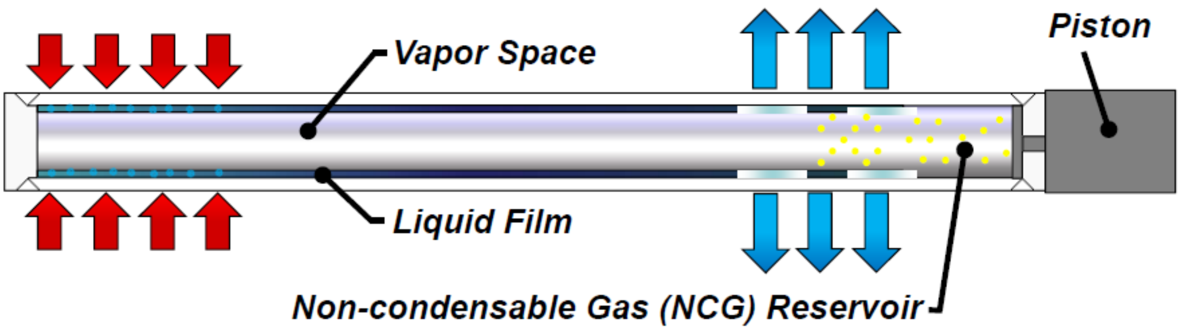


Figure 1. Pressure Controlled Heat Pipe schematic, with the volume modulated with a piston.

All of these requirements can be met with a solar receiver that has Pressure Controlled Heat Pipes (PCHPs) and Constant Conductance Heat Pipes (CCHPs). A 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[4]. A schematic of a pressure controlled heat pipe is shown in Figure 1, where a linear actuator drives bellows or a piston to modulate the reservoir volume.

II. Regolith Processing PCHP/CCHP Concept

The PCHP concept for using solar power to provide oxygen from lunar regolith is shown in Figure 2. The system components include:

1. Two solar receiver heat pipes (SRHPs), one for each regolith processing reactor
2. Two Constant Conductance Heat Pipes (CCHPs), one for each reactor
3. A primary condenser on each SRHP
4. A secondary condenser on each SRHP, with bellows to vary the reservoir volumes

The solar receiver heat pipes are PCHPs with two adjacent condensers. Each SRHP has a linear actuator and bellows, which are used to control the Non-Condensable Gas (NCG) front location, and therefore control the power delivered to each reactor. Moving the bellows in reduces the reservoir volume, and moves the NCG gas front lower in the SRHP. In turn, this reduces the area available for heat transfer, and hence the power transferred from the SRHP to the CCHPs. CCHPs are used to transfer the thermal load from the variable conductance SRHP to the reactor. Supplying heat with CCHPs ensures that a uniform heat flux is supplied to the reactor. Finally, the secondary condensers provide a method to reject excess heat, so that the concentrator can always deliver the full heat load to the SRHP.

The heat pipe orientation shown in Figure 2 assumes that the system is located near Shackleton Crater on the South Pole. In this case, 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.

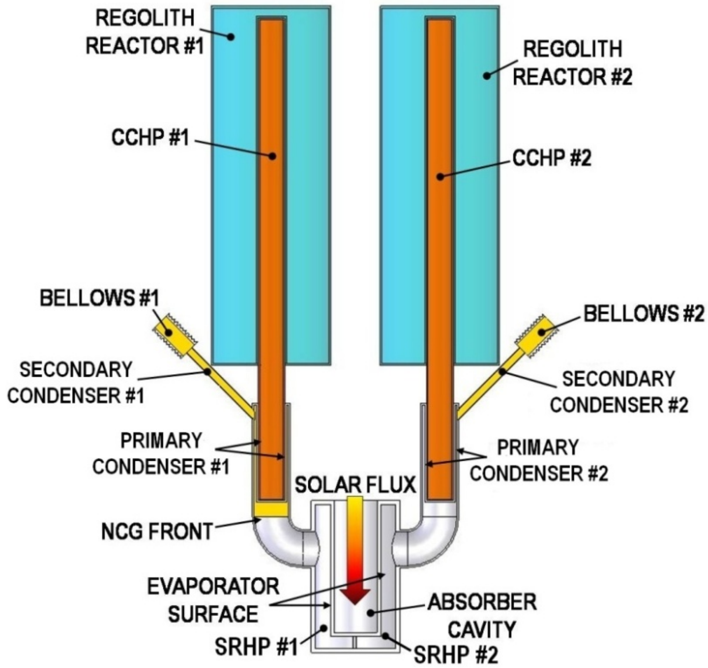
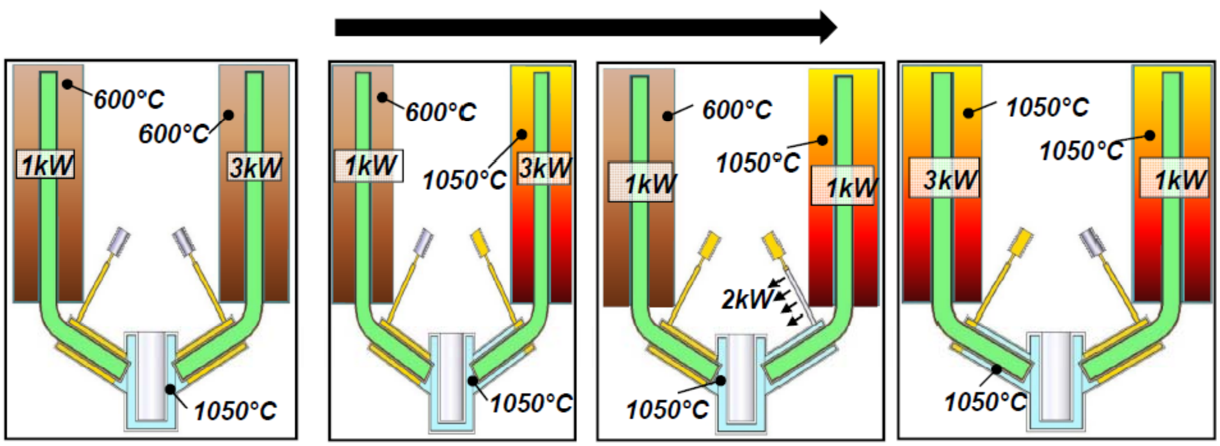


Figure 2. PCHP (SRHP) concept for solar receiver with dual regolith reactors using bellows to vary the reservoir volume.



(a) (b) (c) (d)

Figure 3. The location of the gas fronts is varied to control the power into both reactors. (a) Initial Startup, (b) Move NCG front up on the right hand side to gradually heat up the cold regolith, (c) Dumping excess heat to the secondary condenser on the RHS after the RHS reactor has reached the final temperature, (d) NCG front locations while the RHS is processing, and the regolith is the LHS is heating up.

The projected operational scenario for the start up and operation of a multiple reactor system is as follows:

Step 1: Assume that the SRHP is at 1050 C, and the gas front extends below the CCHP evaporators on both the Left Hand Side (LHS) and the Right Hand Side (RHS) reactors, minimizing the heat transfer to the reactors. At this point, fresh, cold (600°C) regolith is added to the RHS reactor; see Figure 3(a). Without the NCG front, the temperature of the entire system would drop, as heat was rapidly transferred into the cold regolith. By moving the NCG front below the CCHP, the power can be regulated, keeping the SRHP at 1050°C. In the figure, we have assumed that 3 kW is available to heat up the cold regolith.

Step 2: The piston is withdrawn, and the NCG front moves up the CCHP evaporator; Figure 3(b). As the regolith warms up, the driving ΔT between the SRHP and the regolith gradually decreases. By moving the NCG front, the entire 3 kW of heat can still be transferred into the reactor.

Step 3: At some point during the warm-up, the driving ΔT between the SRHP and the regolith becomes so low that the regolith can no longer receive the 3 kW of power available. As shown in Figure 3(c), the NCG gas front starts to expose the secondary condenser, allowing the excess heat to radiate away. Using the secondary condenser to reject waste heat eliminates the requirement to defocus the solar concentrator. Once the RHS reactor is at the operating temperature, only 1 kW of power is required to maintain the temperature.

Step 4: At this point, hydrogen flows through the RHS reactor to produce oxygen. Only 1 kW is required to maintain the RHS, and 3 kW can be used to heat up the LHS reactor. As shown in Figure 3(d), 3 kW is supplied to the LHS. Initially, the entire 3 kW enters the reactor. As the regolith temperature increases, excess heat is radiated from the secondary condenser.

When the LHS reactor is at temperature, the RHS regolith is spent. The LHS reactor is used to produce oxygen. At the same time, fresh regolith is added to the RHS reactor, and the process repeats.

III. Pressure Controlled Heat Pipe for Regolith Processing Modeling - Overview

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.

A complete description of the modeling can be found in Hartenstine, et al. [5] A brief summary is presented here. One solution output from the model is represented in Figure 4 where temperatures and powers of the thermal management system are represented for both reactors simultaneously, but on different plots for clarity.

The two temperatures increase at the start of the cycle, approaching steady state after 4736s. This represents the charging time, $t_{charging}$. The charging time sets the duration of one cycle which is 9437 seconds (2 x $t_{charging}$). During the first part of the charging time the temperature difference between CCHP vapor and regolith is constant because all of the power available ($Q_{charging}$ = 3kW) is supplied through a constant thermal resistance. When the front reaches the end of the primary condenser $t_{front} = 2950s$ the ΔT decreases, so that the power that can be accepted by the regolith decreases. The excess power is then rejected as the NCG front moves up through the primary condenser into the secondary condenser. At the end of the processing interval the regolith is replenished. The new regolith is assumed to be preheated at 600°C. At the beginning of the replenishing time interval, the NCG front is quickly located inside the SRHP 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 secondary condenser (see the step wise increase of the secondary condenser rejected power).

IV. Regolith Processing Thermal Management System Design

The design and control scheme for the SRHP lunar regolith processing system are complex. For this reason, multiple demonstration systems were designed, fabricated and tested. The first two test systems were low-temperature while the remaining two were high temperature utilizing the same envelope materials and working fluids that would be used on the moon. A description of the four test systems follows:

1. Low-temperature, single-sided water/Monel system
2. Low-temperature, double-sided water/Monel system
3. High-temperature, single-sided alkali metal/Haynes 230 system
4. High-temperature, double-sided alkali metal/Haynes 230 system

A. Low Temperature Lunar Regolith Designs, and High Temperature Single-Sided Design

The low-temperature, water/Monel systems are used to demonstrate the feasibility of the system and develop the control scheme without the complexity of using an alkali metal working fluid. The low-temperature water/Monel systems provided a low-cost means to understand performance characteristics and NCG control prior to using alkali metals. The preliminary tests with these systems demonstrated that the NCG could be controlled to effectively throttle the thermal loads to the CCHPs and the lunar regolith.

The next step was to build and test a high temperature, single-sided sodium/Haynes 230 system. This system was used to investigate the control methodology on a high temperature system, to develop a regolith vessel simulator, and to demonstrate the use of high temperature bellows to control the gas front, replacing the pistons used in the low-temperature systems. At the conclusion of the current program, this unit will be used to test different regolith reactor designs for producing oxygen from simulated regolith. The low temperature system design and test results, and the single sided high temperature results can be found in Hartenstine, et al. [6]

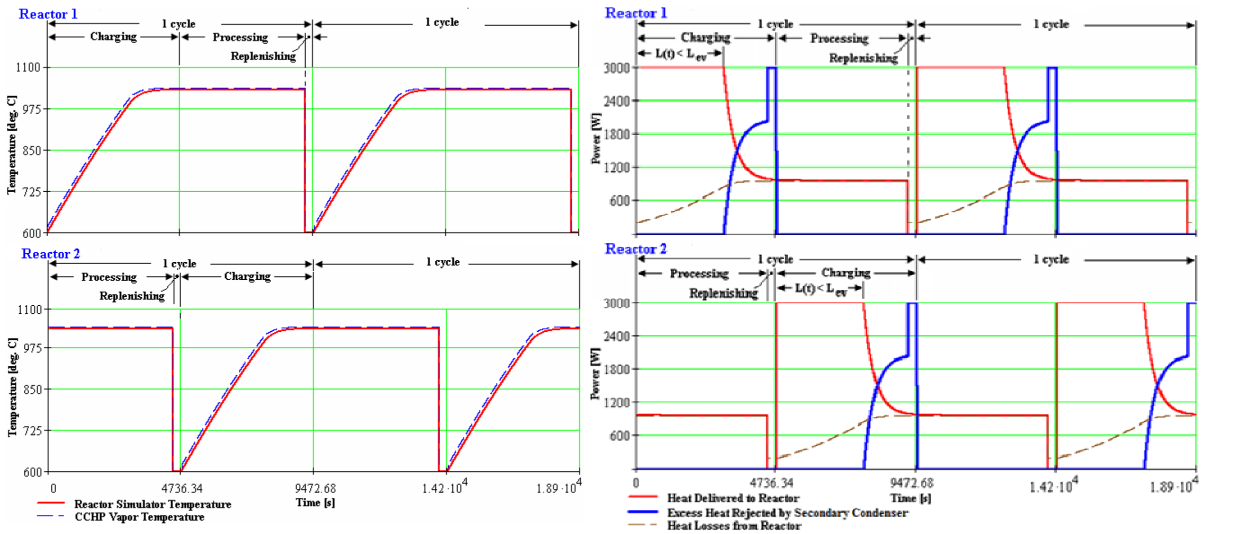


Figure 4. Transient regolith and CCHP vapor temperatures for the two reactors during two cycles (left); Heat flow rate (Q) from SRHP to regolith for each reactor (right).

B. High Temperature System Design

The PCHP concept for using solar power to provide oxygen from lunar regolith is shown in Figure 2. The SRHPs are used to control the gas front location, and therefore control the power delivered to each reactor. The CCHP transfers the thermal load to the reactor from the variable conductance SRHP. CCHPs are used to provide uniform heating to the regolith. The change in the exposed length of the two condensers of each SRHP would vary as the power was transferred. The secondary condensers provide a method to reject excess heat, so that the concentrator can always deliver the full heat load to the SRHP.

The high-temperature double-sided system is scaled down from the full-scale regolith system to allow operation with electrical heaters, rather than a solar concentrator. The full-scale design supplies 4kW of power between the two reactors; 3kW for warm up and 1kW for processing. The scaled down design provides 1.2kW for warm up and 400W for processing. The complete design requirements and capabilities for this design can be seen in Table 1.

Table 1. Haynes 230 final system requirements and capabilities.

PARAMETER	VALUE
Operating Temperature	1050°C
Total Heat Losses*	1000W
Power Required for Warm Up	1200W
Power Required for Processing	400W
Power Input	2600W+

*Heat losses take into account 1inch of Microtherm Super A and 2inch of Microtherm Board Insulation

C. High Temperature System Fabrication

The high-temperature double-sided system has an annular SRHP split in two halves, each with its own side arm, CCHP, secondary condenser and bellows/stepper motor assembly; see Figure 5. The evaporator for the system is located on the exterior surface of the inner vertical pipe. Each SRHP has a separate evaporator, with the vapor space split into two halves by welding a thin Haynes 230 plate on the inside. This plate creates two separate vapor spaces for each side of the evaporator, so that each side of the SRHP has a fixed amount of NCG.

Heat input for the system was provided by a 1700 W Kanthal heater inserted into the solar receiving portion of the evaporator. In addition, supplemental heaters were installed at the base of the solar receiving portion of the evaporator to provide the remainder of the heat. The distance between the regolith reactor simulators that were used for the double-sided Haynes 230 system can be seen in Figure 5. The final system (before insulation was added) is shown in Figure 6.

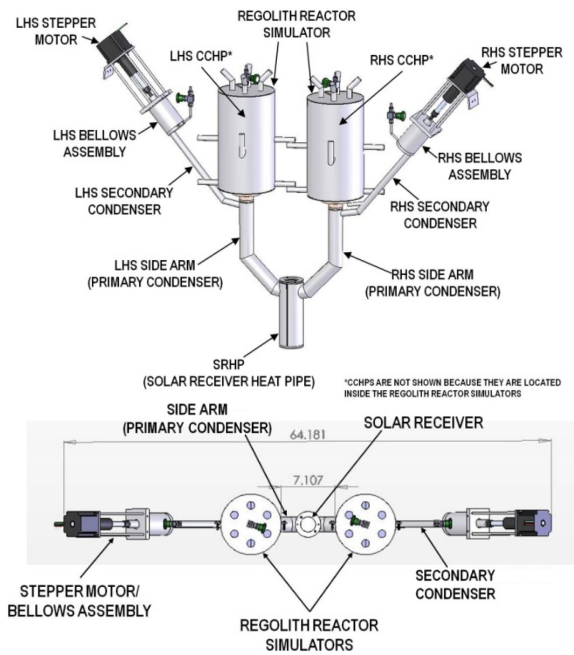


Figure 5. Final High-temperature Dual-Sided Alkali Metal/Haynes 230 system.

V. PCHP for Lunar Regolith Testing

D. Test Setup

Prior to testing, the side arms (primary condensers) were covered with 2 inches of Microtherm insulation. The vertical, annular portion of the system was insulated using the insulation package provided with the ceramic heater. Kaowool was also used as extra insulation and covered the entire system with the exception of the secondary condensers. The dual sided test setup is shown in Figure 7 including the thermocouple locations. The TC distribution is as follows:

- TCs 1 and 26 measure the vapor temperature in the evaporators of both sides of the system.
- TCs 2 through 4 and TCs 27 through 29 measure the vapor temperature in the adiabatic sections of the heat pipes.
- TCs 5 through 12 and TCs 30 through 37 measure the vapor temperature in the primary condenser where the evaporator of the CCHP is located.
- TCs 13 through 17 and TCs 38 through 42 measure the surface temperature in the secondary condensers.
- TCs 19 and 50 measure the vapor temperature of the CCHP condensers.
- TCs 18 and 43 measure the temperature of the bellows assemblies.
- TCs 20 through 25 and TCs 44 through 49 measure the temperature of the "regolith."

The temperature of the "regolith" was measured intrusively by 6 TCs at equidistant locations along the vertical direction inside the "regolith" at the mid distance between the cylindrical case and the central axis. The average value was used to represent the "regolith" temperature.

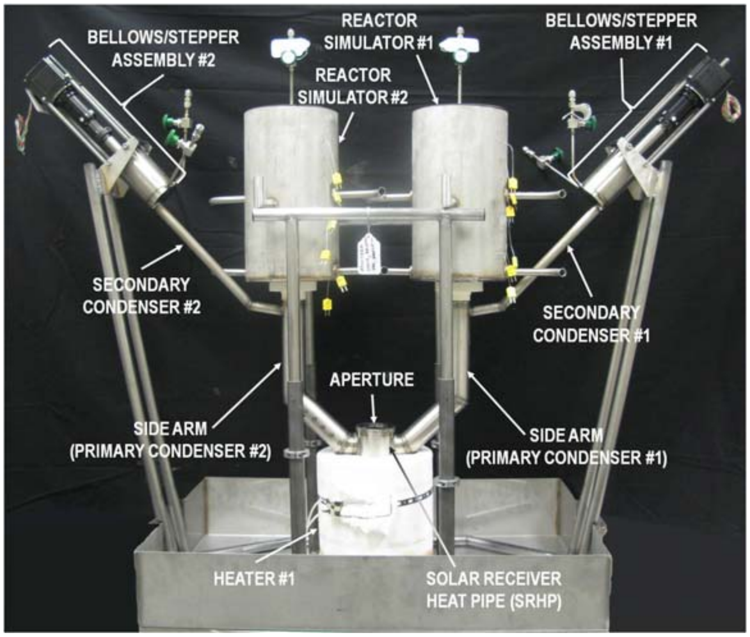


Figure 6. Dual sided Haynes 230 demonstration system test setup.

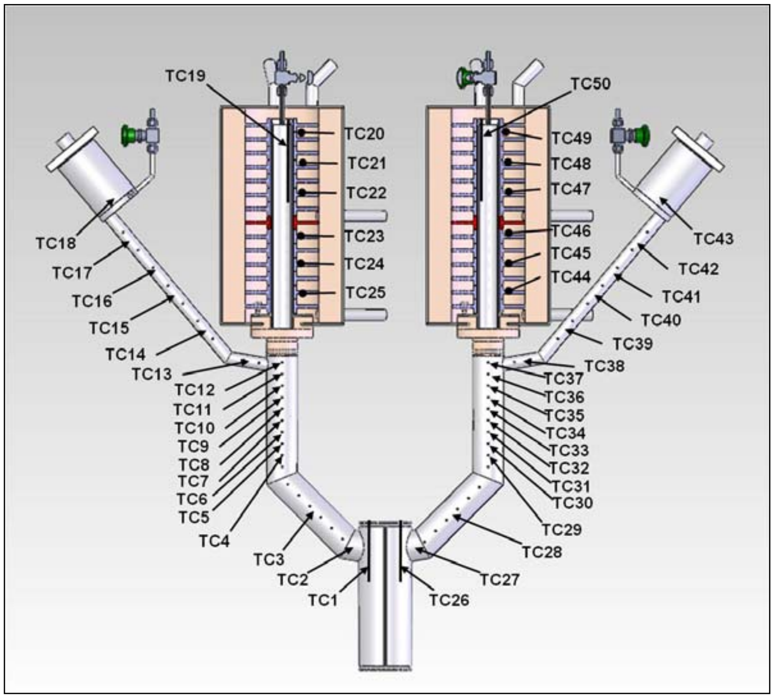


Figure 7. TC map for the dual sided Haynes 230 demonstration system.

E. Test Results

The total power between the two heaters was set to approximately 3.5kW, and was held constant for testing. This power represents the constant power the system would receive from a solar concentrator during actual operation. Figure 8 and Figure 9 represent the transient behavior of the dual sided system during a dual cycle time period. The left hand side of the system can be found in Figure 8, the right hand side of the system can be found in Figure 9 and the sides operating together can be found in Figure 10. The left side of the system was operated through two full cycles (charging-processing-replenish represents one full cycle) while the right side was operated through one and a half cycles. Four temperatures are represented on the primary ordinate axis for each reactor:

- SRHP vapor temperature, TC1 & TC26
- Vapor temperature at the entrance of the secondary condenser, TC13 & TC38
- Vapor temperature in the CCHP condenser, TC19 & TC50 (indicates when NCG front enters the secondary condenser)
- Average "regolith" temperature
-

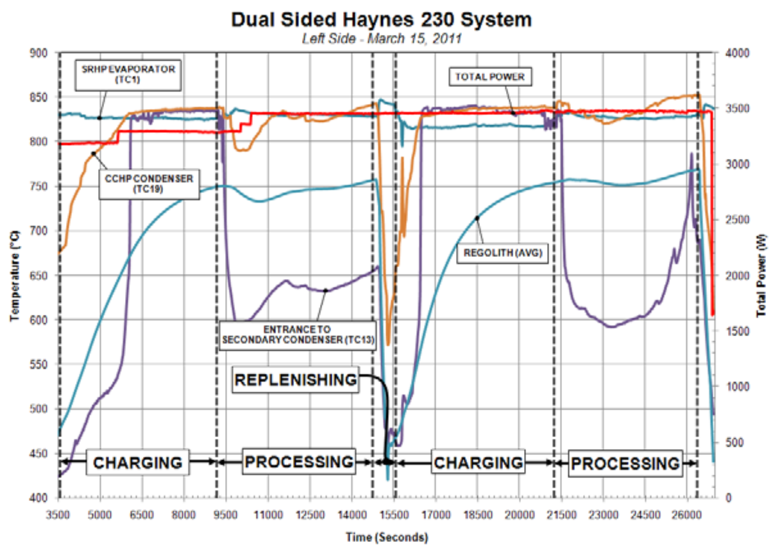


Figure 8. Dual sided Haynes 230 & sodium demonstration system - left side operation.

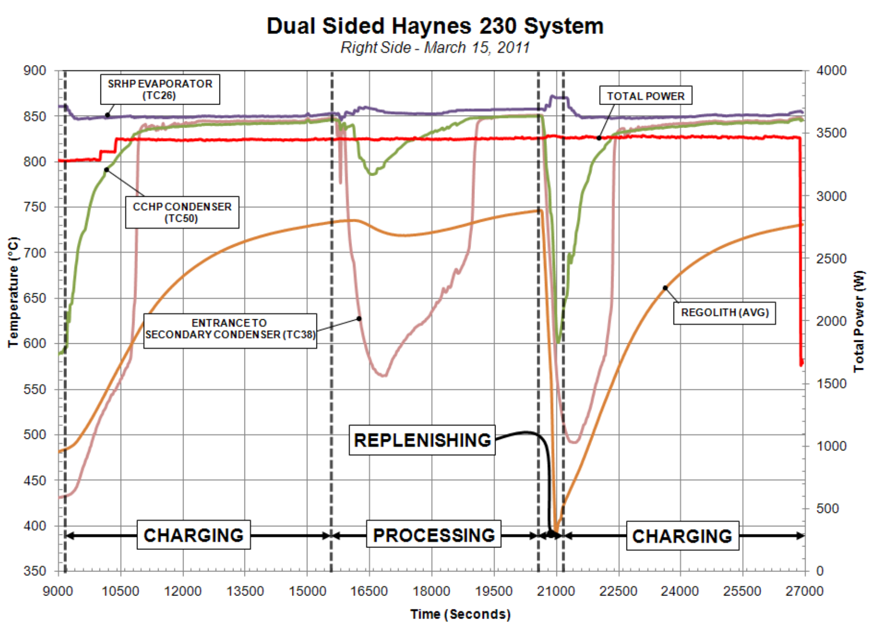


Figure 9. Dual sided Haynes 230 & sodium demonstration system - right side operation.

Testing of the dual sided system was conducted at lower temperatures then the nominal operating temperature of 1050°C. This decision was made to be conservative and protect the heaters from an over temperature condition. A lower operating temperature was also chosen due to the heat losses from the system. An operating temperature of 850°C was chosen. Testing of the dual sided system was performed manually: an automatic control program was not used. The vapor temperature of the SRHP evaporators was observed and the stepper motor was moved to maintain it at a constant value. In a charging state, the stepper motor was moved to pull the NCG into the bellows assembly. At the beginning of a processing state, the stepper motor was moved to push the NCG out of the bellows assembly and into the primary condenser. In the middle of the processing state, the NCG front should be moved to maintain the "regolith" temperature therefore the stepper motor was moved to either push or pull the NCG front. In a replenishment state, the stepper motor was moved to push the NCG out of the bellows assembly to blanket as much of the CCHP evaporator as possible.

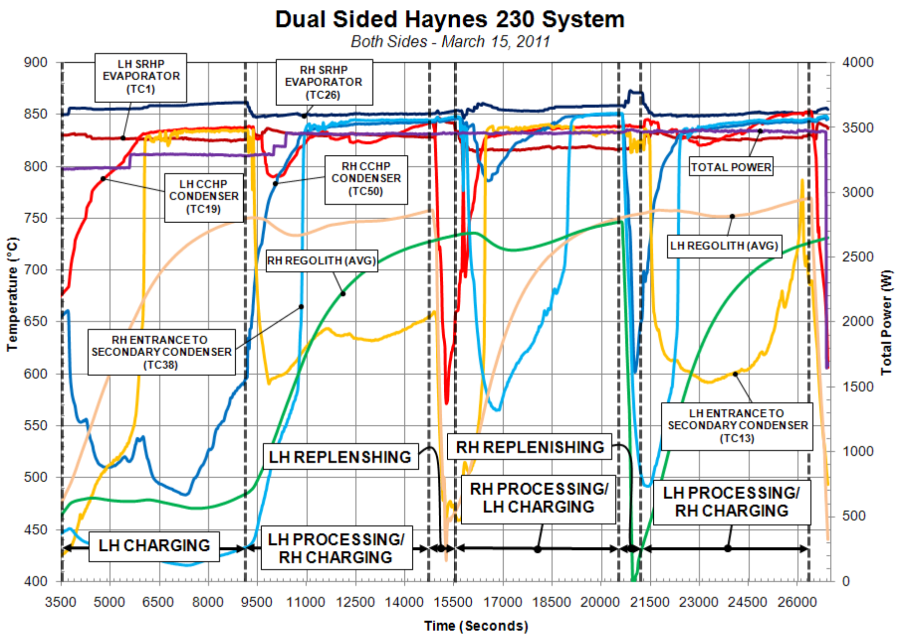


Figure 10. Dual sided Haynes 230 & sodium demonstration system - both sides operating.

The temperature set points were designated as follows:

- Regolith preheat temperature ~ 470°C
- SRHP vapor temperature ~ 850°C
- Regolith processing temperature ~ 750°C

As seen in the figures, the SRHP evaporator vapor temperature was maintained relatively constant for both sides through all stages of the cycle. A ΔT was experienced across the wall that separates the two SRHP vapor spaces. This temperature difference occurs as a result of the heat flux transmitted through the splitting plate from one evaporator to the other because of the unbalanced heat load through the two SRHPs. This ΔT was maintained at approximately 10°C during manual operation. The first charging stage for both the left and right hand sides of the system took approximately 92 to 94 minutes. Charging for the second cycle took approximately 84 to 86 minutes. A ΔT of approximately 100°C was experienced for both sides between the CCHP vapor temperature and the average regolith temperature. The fluidized bed used in a true regolith reactor would greatly reduce this ΔT due to the higher effective thermal conductivity.

Soon after charging starts, a sharp increase in the secondary condenser temperature is experienced in TCs 13 and 38 for the left and right sides, respectively. This is due to the NCG front reaching the entrance of the secondary condenser and thus rejecting the excess power that cannot be conducted into the regolith. At this point in time the ΔT between the CCHP vapor temperature & SRHP vapor temperature is too small and the excess power must be rejected. This can be seen graphically as the CCHP vapor temperature at this moment has reached approximately 830°C for the left hand side and 840°C for the right side. A drastic drop in temperature is observed in the CCHP vapor, regolith and secondary condenser during the replenishment stage of the cycle. At this moment the forced air cooling systems for the regolith reactor simulator was turned on to simulate the removal of processed regolith and addition of new regolith.

The regolith temperature was maintained near constant for all processing cycles for both the left and right hand sides of the system. A slight dip in temperature is observed in both reactors during processing due to more power being transferred to the opposite side to aid in charging, which is the power heavy stage in the full cycle. To summarize, testing of the dual reactor system was completely successful.

VI. Conclusion

Methods to control the thermal loading from a single solar source to multiple lunar regolith oxygen processing reactors were investigated using a thermal management system including PCHPs and CCHPs. Thermal energy was introduced into the aperture of a Haynes 230/sodium heat pipe. The amount of thermal energy was adjusted between the two reactors by varying the volume of non-condensable gas (NCG) in the PCHP using a bellows or piston and stepper motor.

Four separate devices were developed: Low-temperature single and double-sided water/Monel systems, and high-temperature single and double-sided Sodium/Haynes 230 systems. The low-temperature water/Monel systems provided a low-cost means to understand performance characteristics and NCG control prior to using alkali metals. The preliminary tests with these systems demonstrated that the NCG could be controlled to effectively throttle the thermal loads to the CCHPs and the lunar regolith. The next step was to build and test a high temperature, single-sided sodium/Haynes 230 system. This system was used to investigate the control methodology on a high temperature system, to develop a regolith vessel simulator, and to demonstrate the use of high temperature bellows to control the gas front, replacing the pistons used in the low-temperature systems. At the conclusion of the current program, this unit will be used to test different regolith reactor designs for producing oxygen from simulated regolith.

Finally, a high-temperature, double-sided sodium/Haynes 230 system was fabricated. The system is scaled down from the full-scale regolith system to allow operation with electrical heaters, rather than a solar concentrator. It demonstrated the use of PCHPs to switch power between two reactors as required, as well as provide a means to reject excess power. Two full cycles were demonstrated on the left hand side of the system and one and a half cycles were demonstrated for the right hand side. The power input to the system was held constant throughout testing. The dual sided system was successful in demonstrating the ability to utilize a single heat source to transfer power between two separate reactors that are operating out of phase with one another.

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