# Heat Pipe Solar Receiver for Oxygen Production of Lunar Regolith

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**Abstract.** A heat pipe solar receiver operating in the 1050°C range is proposed for use in the hydrogen reduction process for the extraction of oxygen from the lunar soil. The heat pipe solar receiver is designed to accept, isothermalize and transfer solar thermal energy to reactors for oxygen production. This increases the available area for heat transfer, and increases throughput and efficiency. The heat pipe uses sodium as the working fluid, and Haynes 230 as the heat pipe envelope material. Initial design requirements have been established for the heat pipe solar receiver design based on information from the NASA In-Situ Resource Utilization (ISRU) program. Multiple heat pipe solar receiver designs were evaluated based on thermal performance, temperature uniformity, and integration with the solar concentrator and the regolith reactor(s). Two designs were selected based on these criteria: an annular heat pipe contained within the regolith reactor and an annular heat pipe with a remote location for the reactor. Additional design concepts have been developed that would use a single concentrator with a single solar receiver to supply and regulate power to multiple reactors. These designs use variable conductance or pressure controlled heat pipes for passive power distribution management between reactors. Following the design study, a demonstration heat pipe solar receiver was fabricated and tested. Test results demonstrated near uniform temperature on the outer surface of the pipe, which will ultimately be in contact with the regolith reactor.

**Keywords:** Lunar Regolith, Solar Concentrator, Heat Pipe, Hydrogen Permeation, Thermal Fatigue
**PACS:** 44.35.+c, 44.0.+i

## INTRODUCTION

The lunar soil contains oxygen in the form of various oxides, such as silicon dioxide, and calcium, iron and magnesium oxides. 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 (Colozza and Wong, 2006). Realizing this goal would be invaluable for further exploration of the solar system (Findiesen *et al.,* 2008).

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 1625°C. Hot regolith is exposed to methane gas, which produces carbon monoxide and hydrogen. In the second step, the temperature is reduced and the product gases of the first step combine to form methane and water. Water electrolysis comprises the third step, which results in oxygen (Gustafson *et al.*, 2005). 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 carbon reduction, oxygen is produced from electrolysis of this water (Colozza and Wong, 2006). A sodium heat pipe solar receiver operating in the

1000°C to 1100°C temperature range was examined 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.

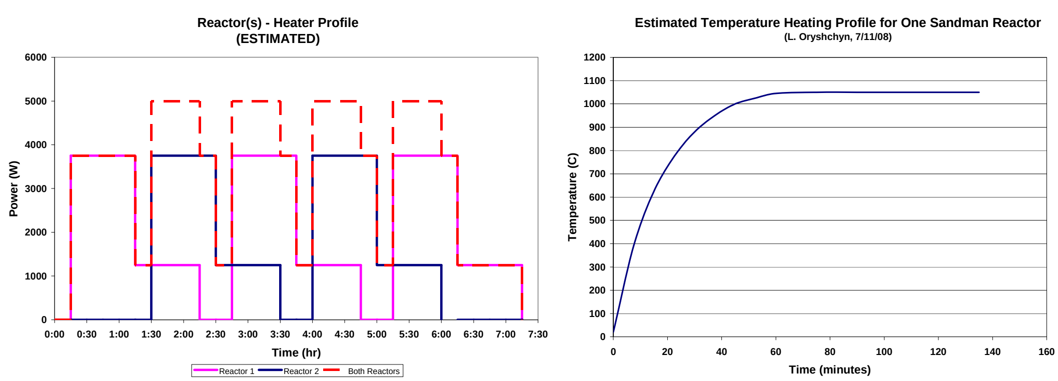
Heat pipes have several advantages for solar power distribution. First, the heat pipe solar receiver can be scaled to increasing heat loads depending upon the solar concentrator design. Second, heat pipes are robust, self-contained, and passive devices. Self-containment allows the heat pipe solar receiver to withstand the abrasive nature of lunar regolith. Design and material selection minimize thermal shock and fatigue resulting from the large temperature swings of the operating environment. The lack of moving parts significantly reduces maintenance. Finally, isothermal operation allows for increased process efficiency. 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.

## SYSTEM INTEGRATION

The solar concentrator determines the direction of the solar flux and the associated heat pipe receiver orientation. In an initial design, the solar flux incident from the lunar horizon will be directed downward into the opening of the solar receiver. The heat pipe solar receiver is positioned vertically with respect to lunar gravity. Design considerations involved a single regolith processing plant that will produce 500 kg of oxygen per year. For a half scale plant, the thermal power for the reactors is 3.08kWth. 1.95kW of this amount is required to heat the regolith batch, and 1.13kW is required to make up for thermal losses of the batch to the environment. The losses are dependant upon insulation designs chosen. The operational conditions are detailed in Table 1. In addition, a terrestrial based system has been established for evaluating the regolith reactor. The heat pipe solar receiver was requested to fit within the geometric boundary of the reactor to simplify test stand integration.

**TABLE 1.** Lunar Regolith Reactor Operational Parameters and Environmental Conditions (NASA/JSC).

| Parameter/Requirement | Value/Range |
|---|---|
| Oxygen Production per plant | 500 kg/year |
| Thermal power during startup (bringing reactor to temperature) | 3.08 kW (half scale plant) |
| Thermal power during steady state (maintaining reactor at temperature) | 1.13 kW |
| Operating temperature | 600-1050°C |
| Sink temperature | -63 to 41 °C (210 to 314 K), Lunar Equator<br>-143 to -61 °C (130 to 212 K), Shackleton Crater |
| Heat flux profile | TBD, but is estimated at 10-20 W/cm$^2$ |
| Temperature range for Hydrogen | 600°C to 1050°C |
| Receiver orientation | Vertical |
| Duty cycle | 70% daylight operation |




(a) (b)

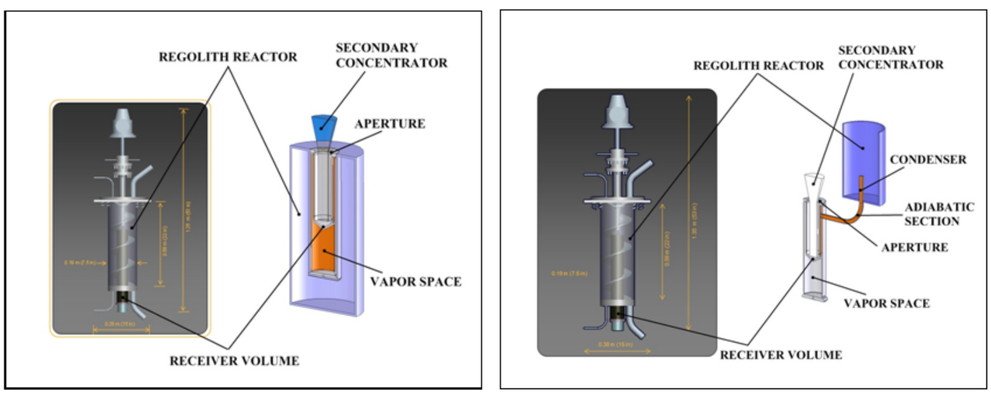
**FIGURE 1.** (a) Regolith Reactor Heater Profile and (b) Estimated Temperature Profile for One Sandman Reactor (NASA/JSC).

Approximated regolith reactor operation parameters were provided by L. Oryshchyn of NASA/JSC. The regolith reactor will ramp up to 1050°C in an hour, process the regolith for an additional hour and 15 minutes, and then dump the processed regolith. Remaining unknown parameters include the temperature profile during the charging and dumping processes. A graph of the estimated temperature heating profile can be seen in Figure 1. One regolith reactor is expected to have a 2.5 hour batch time. Currently, two regolith reactors are expected to function at the same time. In this approach, Reactor #1 runs 3 cycles while Reactor #2 runs 2 cycles. A plot of the approximated reactor heater profiles can be seen in Figure 1.

## Heat Pipe Solar Receiver Concepts

A number of potential heat pipe solar receiver concepts were identified and evaluated by thermal performance, temperature uniformity, integration with the concentrator, and integration with the existing reactor geometry. The concepts evaluated use single or multiple heat pipes to transfer the solar load to the regolith reactor. A total of five potential design options were evaluated: 1) Multiple straight heat pipe configurations, 2) Multiple bent heat pipe configuration, 3) Annular heat pipe design with condenser extending into the regolith reactor, 4) Annular heat pipe receiver contained within the regolith reactor, and 5) Annular heat pipe receiver with an extension leading into the regolith reactor. Concepts 4 and 5 were down-selected for further consideration

Direct illumination of the solar flux into a reactor core may generate non-uniform heating. A common vapor space heat pipe will accept, isothermalize and transfer the non-uniform heat flux solar loading to the regolith reactor for efficient material processing: concepts 4 and 5 exhibit thermal characteristics to meet this requirement. These concepts, shown in Figure 3, can be integrated with the proposed solar concentrator and have a simple geometry, which allows for robust and efficient radiation heat shields to reduce ambient losses. Concept 4 shows the receiver integral with the regolith reactor. Concept 5 shows the receiver with a remote regolith reactor. Ease of integration with the existing regolith reactor is also a key feature, so that the concepts selected could replace the existing electrical heater hardware.

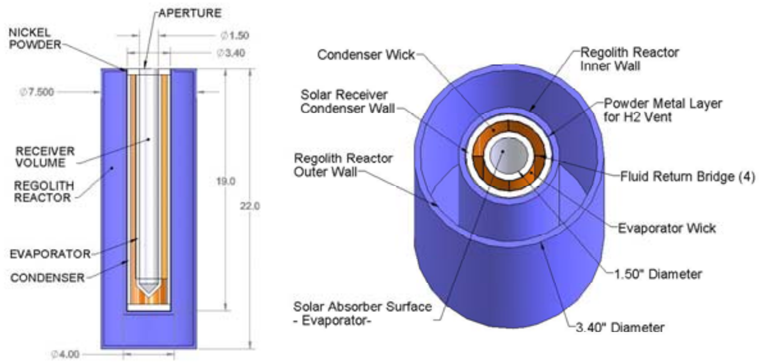



(a) (b)

**FIGURE 2.** Heat Pipe Solar Receiver (a) Concepts 4 and (b) Concepts 5 (NASA/JSC).

## Heat Pipe Solar Receiver Design

The general design details for the heat pipe solar receiver are shown in Figure 3. The heat pipe has a 38.1 mm diameter aperture that is 406 mm in length. This figure also details the location of the heat pipe liquid return wick structure. A design using a screen wick is presented, although a wick using a sintered powder may be required depending upon the incident solar heat flux. This selection depends on the critical heat flux, which is defined for a heat pipe as the heat flux sufficient to prevent the working fluid from re-wetting the evaporator surface. Typical heat flux limits for screen are up to 30W/cm$^2$, while sintered powder metal heat flux limits are approximately ≤ 75W/cm$^2$, depending upon the wick properties and design. Five wraps of 270 mesh stainless steel screen will be bonded to the evaporator and condenser surfaces and connected to each other through 4 liquid return bridges.




(a) (b)

**FIGURE 3**. (a) Initial Heat Pipe Receiver Design Side View with Regolith Reactor and (b) Initial Heat Pipe Receiver Design Cross Section Showing Screen Wick Structure.

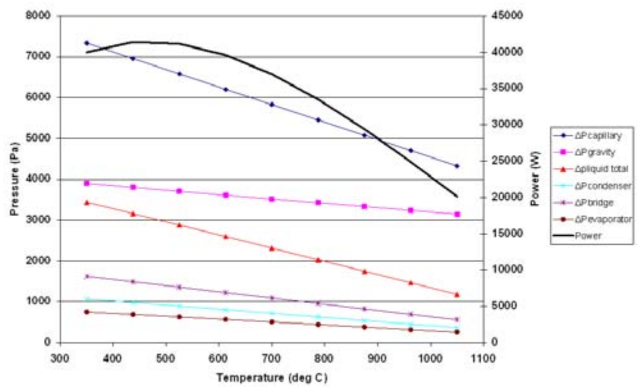



**FIGURE 4.** Heat pipe solar receiver wick design performance parameters.

The heat pipe solar receiver will experience gravitational acceleration of $9.81 m/s^2$ (1 g) on Earth and $1.62\ m/s^2$ (0.165 g) on the moon. Due to the vertical orientation of the solar receiver, the heat pipe wick will need to operate against gravity. In this case the wick will need to self prime at a length of roughly 0.475 m. Calculations were performed to determine the maximum pore size required to prime the wick. For the entire wick to be operational, the selected pore size must be smaller than this maximum. At 1050°C, the maximum pore size required is 64.7µm. 270 mesh screen has a pore radius of 47 µm, allowing the wick to self prime. The capillary pumping capability and the associated pressure drop summary is shown in Figure 4 for the power where the pressure drops equal the capillary capability. It can be seen that the wick properties can adequately meet the 3,000W transport power requirements.

## Hydrogen Permeation

During regolith processing hydrogen is injected into the reaction process at approximately 600°C to 1050°C at approximately 10 psi. An evaluation was conducted and indicated that hydrogen will permeate into the heat pipe: the amount of hydrogen permeating the Haynes 230 wall is constant at 1.3 µg/s for this geometry. Hydrogen that permeates into the heat pipe will collect in the heat pipe condenser, hindering heat transfer. Possible solutions to reduce the hydrogen permeation rate include barrier coatings to minimize permeation, and/or a porous tri-layer wick boundary to vent hydrogen. In the current configuration the regolith reactor can be made as a separate structure surrounding the heat pipe, as shown in Figure 5. The gap between the heat pipe and the reactor can be filled with potential hydrogen barrier coatings. The second method is to fill a gap between the heat pipe and the reactor wall with a thin layer of porous powder metal. The thin layer of powder metal will fill the length of the heat pipe as shown in Figure 5. The end of the gap will be open to the vacuum of space. During operation the hydrogen will permeate through the reactor wall and into the powder metal. The hydrogen will permeate out of the powder particles and form molecular hydrogen due to the large surface area of the powder and the low partial pressure at the powder surface (Anderson *et al.,* 1995). The molecular hydrogen is subsequently vented to space. This significantly reduces hydrogen permeation into the heat pipe. One issue with the porous powder metal hydrogen permeation boundary is the temperature difference across the porous layer. Calculations were performed to determine the $\Delta T$ across the gap, i.e., what solar receiver temperature is required to meet the 1050°C regolith reactor temperature requirement. With a transferred power of 3.4 kW and a target reactor temperature of 1050 °C, the sodium vapor temperature would be 1056.3 °C.

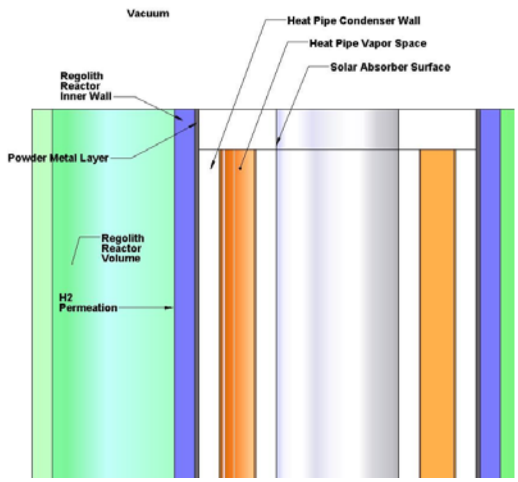



**FIGURE 5.** Solar Receiver Integration Layout.

## Structural Analysis

Structural analyses were performed on the preliminary solar receiver design based on the stresses due to the vapor pressure of sodium at various temperatures. The stresses were then used to estimate the creep time to rupture values for the Haynes 230 material at temperatures from approximately 1000°C to 1200°C. The creep analysis was performed for both the inner and outer cylinders as well as both end caps in the heat pipe. The Larson Miller Parameter (LMP) was used to make a conservative estimate of the lifetime of the heat pipe operating at varying temperatures and stresses (Blake, 1985). This parameter relates expected lifetime prior to rupture with temperature and pressure. Data was taken from the Haynes 230 brochure provided by Haynes International as well as additional Haynes 230 data that was provided for higher temperatures. Data was also provided by Shingledecker *et al.* (2004). The LMP value was then used to calculate the time to rupture using equation (1):

$$t_R = 10^{\frac{LMP}{T+273.15} - C} \tag{1}$$

where:

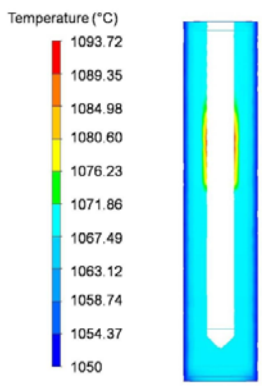
| | | |
|---|---|---|
| $t_R$ | = | Time to Rupture (hours) |
| T | = | Temperature (°C) |
| LMP | = | Larson-Miller Parameter |

A constant C of 17.6 was used for the Larson Miller calculations. Calculations were performed for all portions of the heat pipe. At 1204°C the outer pipe will experience creep rupture failure after roughly 25 hours. This is the greatest concern in the structural analysis. However, the designed heat pipe will be operating at roughly 1050°C. At 1050°C the outer pipe will experience creep rupture failure after $1.23 \times 10^5$ hours, the inner pipe will experience creep rupture failure after $4.17 \times 10^5$ hours, and the flat end cap will experience creep rupture failure after $2.08 \times 10^5$ hours. The lunar regolith reactor is expected to operate for 6,100 hours a year. According to these results, failure due to creep rupture will not be a concern, as it will take $1.23 \times 10^5$ hours before any part of the heat pipe is in danger of such failure. Even though the creep rupture analysis indicates acceptable life, additional work will be conducted to evaluate the high temperature characteristics in greater detail.

## Heat Pipe Solar Receiver Thermal Analysis

There are a number of potential concentrators that are being considered, including an inflatable design and rigid designs with single or multi-faceted mirrors and refractive secondary concentrators. Testing of a refractive secondary concentrator was conducted at NASA (Geng and Devarakonda, 2002). A refractive secondary concentrator was inserted into a rhenium cavity and tested using the lamps from Tank 6 at NASA/GRC. Specific heat flux values over eight discrete locations along the rhenium cavity length were established. At a solar power setting of 1150W, the solar flux reached a maximum of approximately $10W/cm^2$. A thermal analysis was performed for the designed heat pipe using Blue Ridge Numerics CFDesign. Boundary conditions were determined from the refractive secondary test data. This data was based on a solar receiver length of roughly 8 inches and a secondary concentrator of roughly the same length. Based on this data, the heat flux past the first 8 inches of the solar receiver was assumed to be minimal.

The thermal model includes the outer wall of the receiver, the nickel powder metal wick, and the regolith reactor inner wall. The heat transfer coefficient on the inner wall of the reactor was approximated as there is no data currently available for the regolith/hydrogen mixture. The model used a heat transfer coefficient of $100,000\ W/m^2K$ at 1050°C. Figure 6 shows the results and boundary conditions of the thermal analysis. The highest temperature reached is 1093.72°C at 7.1 inches into the heat pipe solar receiver. All of the heat that is applied by the secondary concentrator is contained within the inner pipe. Calculations were performed to determine the pressure and temperature drop within the vapor space. The values were so low that the temperature drop within the pipe was negligible.




| Location | Boundary Condition |
|---|---|
| 1 | T=1050°C, h=0.1 $MW/m^2K$ |
| 2 | k=0.03 $W/cm^2$ |
| 3 | k=0.13 $W/cm^2$ |
| 4 | k=0.27 $W/cm^2$ |
| 5 | k=0.54 $W/cm^2$ |
| 6 | k=1.35 $W/cm^2$ |
| 7 | k=2.70 $W/cm^2$ |
| 8 | k=5.93 $W/cm^2$ |
| 9 | k=15.9 $W/cm^2$ |
| 10 | k=22.9 $W/cm^2$ |
| 11 | k=27.0 $W/cm^2$ |
| 12 | k=28.3 $W/cm^2$ |
| 13 | k=24.3 $W/cm^2$ |
| 14 | k=20.2 $W/cm^2$ |
| 15 | k=21.0 $W/cm^2$ |

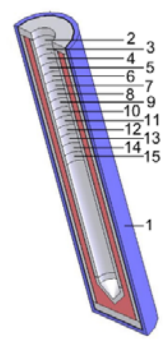



**FIGURE 6.** Thermal Analysis Results.

## Multiple Reactor Design

Design concepts were also evaluated that incorporate a single solar receiver supplying varying power to two reactors, compared to the designs above which have a single solar receiver supplying power to a single reactor. Heat pipes can be used to control the transfer of thermal loading from one reactor to the other reactor. Initially, 4kW of power would be transferred into the first reactor at startup. Once this reactor reaches 1050°C, 3kW would be switched to the second reactor. 1kW would continue to be transferred to the first reactor to maintain processing temperature. After the second reactor reaches 1050°C, 2kW is switched back to 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. A reduction in solar input may have to occur to handle the cross-over so that overheating does not occur. A conventional constant conductance heat pipe design would not meet the requirement to control the thermal loading between multiple reactors using a single solar receiver. Instead, variable conductance heat pipes or pressure controlled heat pipes would be used.

A Variable Conductance Heat Pipe (VCHP) is similar to a conventional heat pipe, but has a reservoir and controlled amount of non-condensable gas (NCG) inside the reservoir. A VCHP controls thermal energy transfer by varying the amount of condenser available to the working fluid, by compressing and expanding the NCG. A Pressure-

Controlled Heat Pipe (PCHP) is similar device that permits control over heat pipe operation by varying the gas quantity. The PCHP differs from a VCHP in the aspect that it contains a reservoir as well as a pump to modulate the quantity of gas in the heat pipe. By varying the quantity of gas in the heat pipe the amount of active condenser is controlled. For the solar receiver application transferring back and forth between multiple reactors, a PCHP could be used in a manner similar to that shown in Figure 7. The components would include a single solar receiver with two PCHP condensers and reservoirs, and two constant conductance heat pipes. The PCHPs would control the gas front and subsequent power delivery to each reactor. The CCHP would 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 power is transferred.

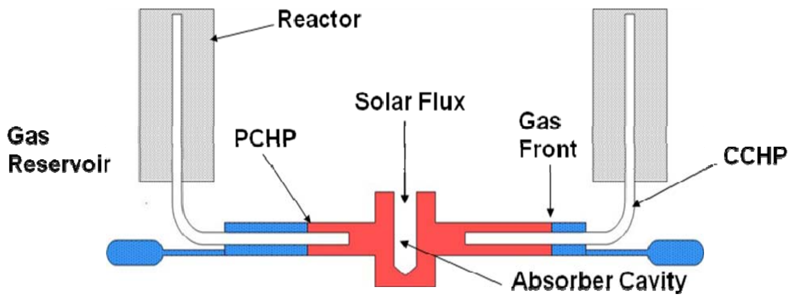



**FIGURE 7.** PCHP Concept for Solar Receiver with Dual Regolith Reactors.

## DEMONSTRATION HEAT PIPE

A representative solar receiver heat pipe was designed and fabricated as a proof-of-concept test article. The demonstration heat pipe has an annular configuration, and was manufactured from Haynes 230 with a stainless steel screen wick, and with sodium as the working fluid. The heat pipe is oriented horizontally for ground testing, to allow it to fit into the NASA MSFC test rig. The completed heat pipe was instrumented and insulated to minimize heat loss to the surroundings. A photograph of the instrumented assembly is shown in Figure 8a. Figure 8b, right shows the heat pipe operating at approximately 1050°C. Electrical power was input to the Kanthal heater and the temperature profile recorded using a data logger. The power was increased until the heat pipe vapor temperature reached 1050°C. The thermal profile for the demonstration heat pipe assembly is shown in Figure 9. The thermal profile plots the individual thermocouples and the approximate electrical power input to the heater. The data indicates that the heat pipe is nearly isothermal. At 1050°C, the difference between the maximum and minimum temperature across the outside diameter of the pipe was 5-6°C. The inner wall temperature measured approximately 1065°C, with a 1050°C vapor and outer wall temperature, indicating that the screen wick structure was sufficient to wet the evaporator surface.

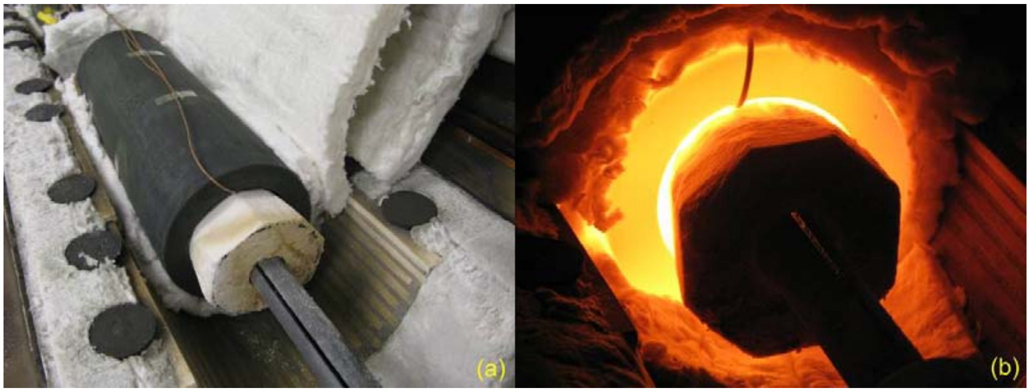



**FIGURE 8**. (a) Demonstration heat pipe test set up and (b) demonstration heat pipe operating at 1050°C using a Kanthal heating element.

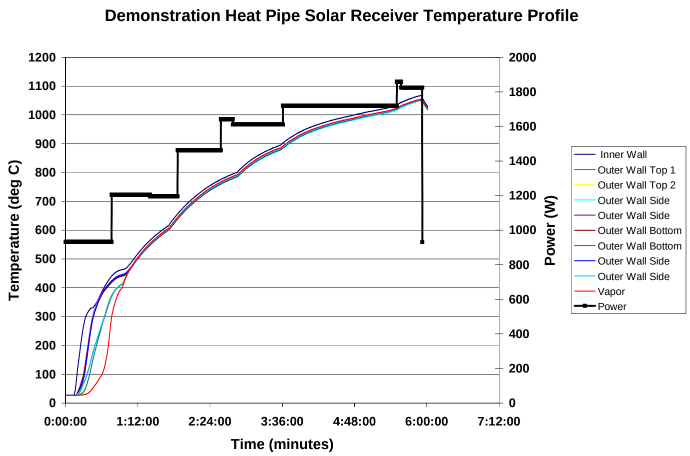



**FIGURE 9.** Thermal profile for the demonstration heat pipe.

# CONCLUSION

A means to extract oxygen from the lunar soil is required for Earth-independent habitation on the moon. A hydrogen reduction process is being considered, using the solar thermal energy to heat and process the lunar material. High temperature heat pipes were evaluated for solar power distribution to the regolith process reactors: two heat pipe solar receiver designs were developed. Each design is an annular heat pipe design with a common vapor space. In one concept, the heat pipe receiver is contained within the regolith reactor. Incident solar flux is distributed into an aperture that forms the inside diameter of the heat pipe. The solar energy is transferred nearly isothermally to the regolith process. In the second concept, the same heat pipe design is used, except the thermal load can be transferred to a remote location. Heat pipe geometry, wick structure design, and mechanical stresses due to sodium vapor pressure were determined. In addition, hydrogen permeation into the heat pipe was addressed along with potential methods to reduce the permeation rate. Methods to control the thermal loading to from a single solar source to multiple reactors was evaluated using VCHP's and PCHP's. In addition, a demonstration annular heat pipe was designed, fabricated and tested up to 1050°C.

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