A review of lunar surface for Photovoltaic systems and a possible cooling method

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Abstract The long envisioned lunar solar power station would require an efficient cooling system that works by exploiting the features of the lunar environment . Firstly, the efficiency of PV cells with respect to temperature has been discussed. The basic features of the moon are then discussed by presenting the results of various studies along with suitability of PV cells in particular regions. Various favorable anomalies were observed for placement of PV Cells and possible habitation. Finally, a possible passive cooling system and its fundamental theory is presented

Keywords ***Crater, Loop Heat Pipe, evaporator, lunar , illumination***

1. Introduction

With the conventional energy systems becoming useless in the future it's inevitable that we will have to look for new sources of energy, preferably sustainable. And terrestrial solar, geothermal, hydro and wind will not be feasible for the large energy demand due to their intermittency on earth. Moreover Earth's atmosphere will have drastically changed by the time we exhaust out conventional sources due to their polluting qualities, painting an unclear picture of how it will affect the renewable sources. If the future is uncertain, our best hope would be to look for energy beyond Earth into space. Solar energy is currently the only feasible source we can collect with our technology beyond earth. Lunar solar power system is a possible way to meet our energy needs envisaged my many. Due to no atmosphere, PV cells on moon will be able to collect unhindered solar radiation and generate much energy than here on earth. Furthermore, with the advancement in microwave and rectenna technology, the energy could be send back to earth with a beam. Also silicon is abundantly available on the moon (Ignatiev et al. 2004) and the cost of transporting huge amount of materials from Earth would be reduced to just manufacturing equipments. Lunar solar power systems could also be the only source for power if mankind ever decides to settle on moon. However, PV cells on moon could face many problems and the main would be heating up due to solar radiation and no convective cooling. They have been known to significantly reduce in efficiency with increase in temperature. This paper gives an overview of the lunar surface by presenting the results of different studies over the years about the lunar conditions and a possible Loop Heat Pipe passive cooling method has been discussed by presenting the results obtained in different papers. This paper is also a prelude to the author's possible future research work.

2. Photovoltaic Cells and the Lunar Geology

The most important parameter of a solar cell is its efficiency. It is the electrical power output to the solar power input to the solar cell. The efficiency depends on many factors like low photon energy, excess photon energy, reflection, obstruction, curve factor, series resistance, shunt resistance and temperature[1]. Overall 48% of the incident power is converted into heat. So theoretically around 656 W/m^2 should be converted to heat in the lunar equatorial region. Large temperature performance loss is a matter of concern as shown in Fig. 1[2] and it can severely affect in lunar working environment which can heat above 100° Celsius. However, it may be possible to overcome those by studying and taking advantage of the geology of the moon.

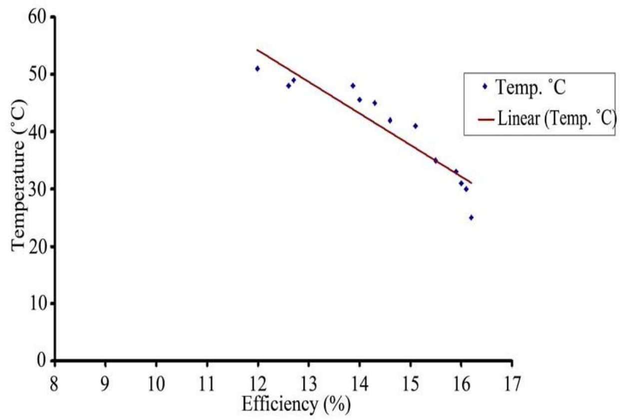

Fig. 1 Temperature vs efficiency curve for a Si solar cell

This equation gives the efficiency of solar cell in terms of voltage (V_{oc}) , current (I_{sc}), fill factor(FF) and input power (P_{in}):

$$\eta = \frac{VocIscFF}{Pin}$$

Increase in temperature reduces the band gap of a semiconductor, and therefore lower energy is needed to break the bonds. As a result the current slightly increases but the parameter most adversely affected is the open- circuit voltage as shown in Fig. 2[3] , so over all the power output decreases

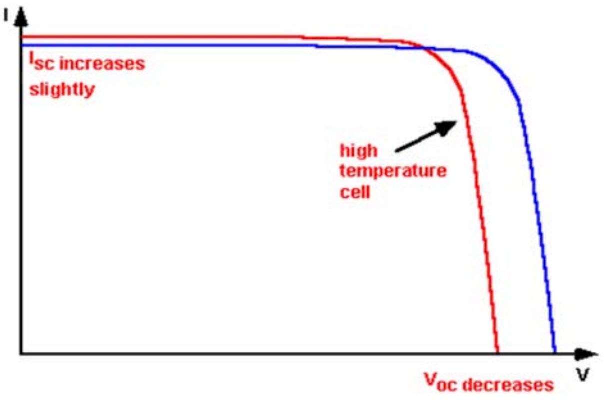

Fig. 2 The effect of temperature on the IV characteristics of a solar cell.

3. **Surface features of moon for PV power stations.**

Analyzing the lunar features are important for future human habitation and power station placements. A PV power station's ideal place would be a place with high direct illumination and favorable temperature for maximum efficiency but we are going to find out in the further texts that an ideal place with the mentioned characteristics for PV power station is almost impossible on moon and therefore further geological features would have to be exploited to gain the full benefit of the lunar surface. The fact that a day in Moon equals 28 Earth days, that is 14 days of sun and 14 days of darkness plays an important factor on the availability of power and possible habitation (Cohen 2002). The Moon receives the same flux of solar radiation as the Earth and The Lunar Surface Effective Solar Illumination(LESI)[4] can be given by :

$$LESI = \frac{S_0 \cos i}{R^2{}_{SE}}$$

where S_0 is solar on moon, *i* is the solar radiation incidence angle and R_{se} is the sun earth distance in astronomical units. The extremely negligible atmosphere of the Moon makes the surface incident solar radiation to be controlled by its shape, the length of the lunar day and the tilt of its spin axis (Paige 2010). And this affects the surface temperature, which depends primarily on the location's latitude and longitude and on the Sun angle on the local sky. Temperature generally decreases on Moon from equator to poles following a cosine law. Both these changes can be approximated by the relation[5] :

$$T = 373.9cos^{.25}\theta sin^{.167}\varphi \;\; K$$

Where T is the temperature in Kelvin, θ is solar angle above lunar horizon and φ is moon's latitude in degrees. There have been many proposals for lunar base at one of the poles where there is fair amount of solar energy (Cohen 2002). Polar locations can have constant sun light in the summer which can last for many months followed by darkness for the rest of the year. Some highly elevated places like crater rims can have steady illumination for 70 percent of the winter (Christie et al. 2008). Recent studies indicated that certain regions on the rims of craters, ridges received illumination for almost 98% of the time. At north pole, many places on the rim of Peary crater were illuminated for the summer day and there are also some locations at the polar regions which has continuous illumination during an year. One such region is near the rim of Shackleton crater in south pole (88.75° S) which experiences solar illumination for almost 313 days in an year (Bussey et al. 2010). The average temperature around this crater is found to be 90 K [6]. Figure 3 shows the surface temperature mapping by Diviner.

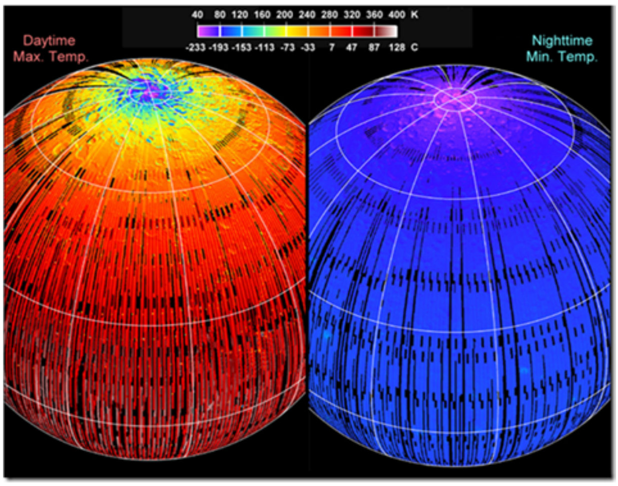

Fig. 3 Diviner channel 8 moon surface temperature (www.diviner.ucla.edu)

There are many polar crater floors which never experiences sunlight with temperature around 80 K (Seybold 1995). Craters within craters, which are also known as double-shaded craters, have areas which are even colder, and in most of the cases temperatures that must not go above 50 K (Ryan et al. 2008). Studies by Carruba and Coradini shows that temperatures of single-shaded craters are in 83-103 K range (Langseth et al. 1976). They also found out that double-shaded craters can have temperatures within 36-71 K (Ryan et al. 2008). The NASA's Lunar Reconnaissance Orbiter analysed the least summer temperatures in the darkest of craters at southern pole to be near 35 K. In the north, the temperature was about 26 K

Temperature measurements from Apollo missions at 20° and 26° N latitude ranged from 102 K to 384 K with an average of 254 K. The average temperature measured 35 cm deep of the Apollo sites was 40-45 K warmer than the lunar surface. Temperatures at depths greater than 80 cm showed no appreciable variations throughout the year (Paige 2010). Temperatures measured at 100 cm deep were about 252 K at Apollo 15 site (26° 5' N latitude) and 255 K at Apollo 17 site (20° 10' N) (WOTM 2010). And at a depth of 1 m the temperature is constant at about 220K. This makes the lunar subsurface a potential place for habitation and excellent heat sink (Heiken et al. 1991; WOTM 2010; Paige et al. 2010).

Heating up due to solar radiation will be the main factor affecting the efficiency of the solar cells[5]. So, the datas provides very interesting perspectives with respect to solar energy utilization for lunar habitat. The poles where there is sufficient illumination with craters nearby could serve as a good sunlight source as well as excellent cooling heat sinks for the PV Cells. Furthermore at the equator where there is maximum illumination, the underground of moon could serve as the cooling heat sink.

4. Potential Cooling Methods

A number of different active and passive systems are currently being applied in spacecraft thermal control. By applying active or passive cooling methods (Fortea 1981; Royne et al. 2005) the intense solar cell temperature at day can be brought down to ambient level as in earth. However while developing a plan we much first lay emphasis on passive techniques rather than active since active requires energy input. And since some areas in moon like underground, craters and poles could serve as potential cooling sinks, passive systems should be first investigated and researched upon.

One of the most common passive system is the fluid loop system. A fluid loop system is basically a closed loop, in which a liquid coolant is circulated. The coolant is first heated by the heat sources, and then pumped to the heat sink where it is cooled. Fluid loops are lighter and provide better heat transfer characteristics than elements designed for conductive heat transfer, and are thus frequently applied in complex space heat cooling systems. Space-qualified mechanical pumps for fluid loops have also been developed at ESA since the late 1970s. Mechanical fluid loop systems with single phase or two-phase cooling loops compatible with a wide variety of fluids are also now available. A simple fluid loop system is shown in Fig. 4 [6]

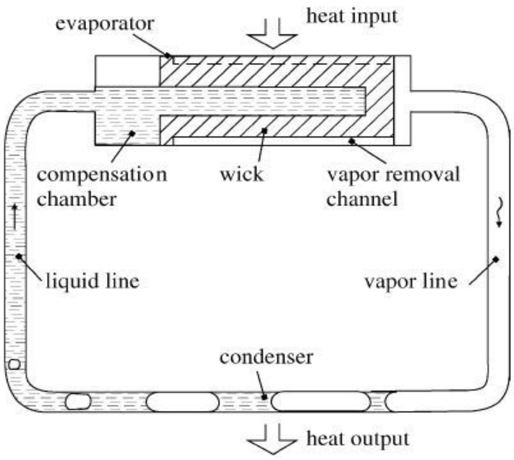

Fig. 4 Schematic view of a fluid loop system

Another popular passive system is heat pipe. A heat pipe is a sealed tube that is partly filled with a liquid. One end of the pipe is connected to a heat source and the other a heat sink. If the temperature of heat source is higher than the sink, liquid available in the heat source reservoir will evaporate, and a stream of vapor will start flowing to the heat sink end, where the vapor condenses and returns back to liquid state (Silverstein 1992). A wick is utilized and capillary action is used to return the condensate back to the heat source end. A simple schematic of a heat pipe system is shown in Fig. 5

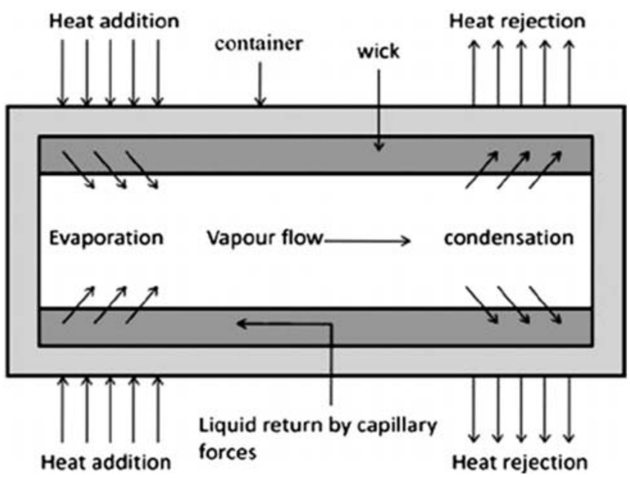

Fig. 5 Schematic view of a heat pipe

Fluid loop and heat pipe systems are both designed to transfer heat from a hot end and both works according to the same fundamental principle of surface tension and capillary action and none of these systems can operate if the heat sink temperature is greater than the heat source temperature. However, LHPs are different in construction to heat pipes and have the advantage to provide heat transfer over fairly long distances and efficiently work against gravity. Many designs of LHPs, large LHPs to small LHPs have been developed and successfully operated in a wide range of conditions both in ground based and space applications.

4.1 LHP Theory

Theoretical analysis of operation of loop heat pipes is given in numerous publications [12–21]. Below are some basic elements of LHP theory. The operation of LHPs is based on the same processes as those in heat pipes. However, they are structured in quite a different way. Firstly, the wick, which in LHP plays a more complicated role. To get a view of these functions a LHP is presented in Fig. 6 [21]. While inactive, the free surface of the working fluid is at a level A-A located in the liquid line and evaporator as in communicating vessels. At this moment wick is saturated with a liquid, and vapor line and the condenser are fully filled. If heat is applied to the evaporator, the liquid begins to boil and evaporate from the wick both in the evaporation zone as well as in compensation chamber. As the wick possesses a thermal resistance, the temperature and pressure of vapor in evaporation zone which is closer to the evaporator wall become higher than the compensation chamber's [9]. The wick so serves as a ‘‘thermal lock’’. At the same time hot vapors cannot go into the compensation chamber through the saturated wick due to capillary forces which hold the liquid. So another function of the wick is that of a hydraulic lock. The developed pressure difference displaces the working fluid from vapor line, the condenser and filling of the compensation chamber. Here, three interfaces may exist in the LHP simultaneously: in the vapor zone, condenser and in the compensation chamber.

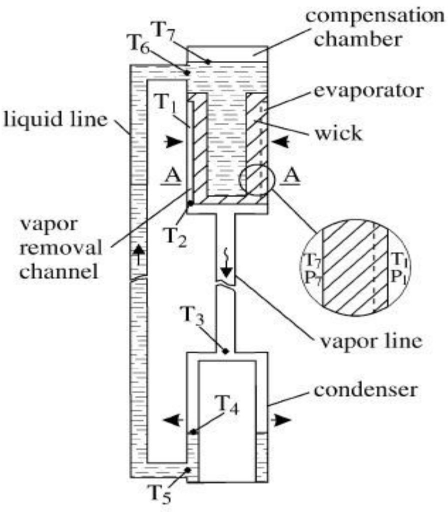

Fig. 6 Analytical LHP scheme

A typical kind of operation characteristics obtained by an experiment for a water and ammonia LHPs is presented in Fig. 7[21]. It can be seen that the dependences have an ambiguous character. Firstly, with increasing heat, the vapor temperature decreases, and then quasi-stabilization. It is because of the simultaneous action of these factors: liberation of the condenser at the expense of gradual liquid displacement into the compensation chamber, lowering of temperature of the compensation chamber with increasing in the mass flow rate of cold fluid that enters it and the rise of the heat intensity in the evaporator. In this domain of heat loads LHPs works with a variable conductance. When the compensation chamber completely fills with the fluid, condensation surface stops changing then a constant conductance regime takes over.

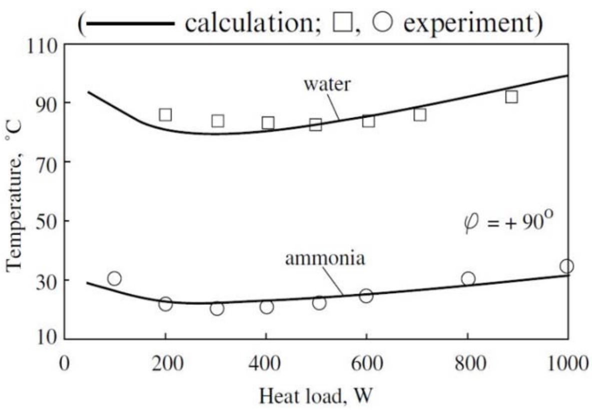

Fig. 7 Evaporator temperature vs heat load for NH_3 and H_2O

The first crucial step in selecting a LHP working fluid, envelope and wick material is to find out the working temperature range. Saturation conditions are very important, that is the heat pipe contains both liquid and vapor. Because of this, the selected fluid should only operate between the freezing point and the critical points.

Table below shows minimum and maximum working temperature ranges related to some fluids and also the compatible materials [17]:

Table 1: Min and Max operating temperatures of working fluids and suitable materials

Minimum operating temperature(Celsius)	Maximum operating temperature(Celsius)	Working fluid	Envelope materials
-271	-269	Helium	Stainless steel, Titanium
-258	-243	Hydrogen	Stainless Steel
-246	-234	Neon	Stainless Steel
-214	-160	Oxygen	Aluminum , Stainless steel
-203	-170	Nitrogen	Aluminum, Stainless steel
-170	0	Ethane	Aluminum, Stainless steel
-150	40	Propylene	Aluminum, stainless steel, Ni
-100	120	Pentane	Aluminum, Stainless steel

-80	50	R134a	Stainless steel
-65	100	Ammo-nia	Alumi-num, steel, stainless steel, Nickel
-60	~ 25 - 100	Metha-nol	Copper, stainless steel
-50	~100	Acetone	Alumi-num, stainless steel
-50	280	Toulene	Steel, stainless steel, Titanium, Cop-per-Nickel
20	300	water	Copper, Monel, Nickel, Titanium
100	350	Naph-thalene	Alumin-ium, Steel, stainless steel
200	400	$AlBr_3$	Hastel-loys
400	600	Cesium	Stainless steel, Inconel

The moon can provide a heat sink with temperature near -203 Celsius at polar craters and near to -18˚ Celsius and -53˚ Celsius at depths of 100 cm and 1 m respectively with further lower temperatures below up to a limit from where temperature rises to the core. To exploit the full benefits of those places Pentane, ammonia, methanol, acetone and toluene are the best working fluids according to the table.

4.2 Large and powerful LHPs

Institute of Thermal Physics, Ural, Russia design a LHP with two compensation chambers at the evaporator ends [18] with overall 2m long made of stainless steel [19]. The evaporator was 24mm in diameter and the active-zone had a nickel wick with a break-down pore radius 1.1lm. The condenser was 310mm in length and 24mm in diameter . It was made like a pipe-in-pipe heat exchanger and its inner and outer surface were cooled by flowing water at 17 ± 1_C. The vapor and the liquid line had flexible inserts 500mm long.

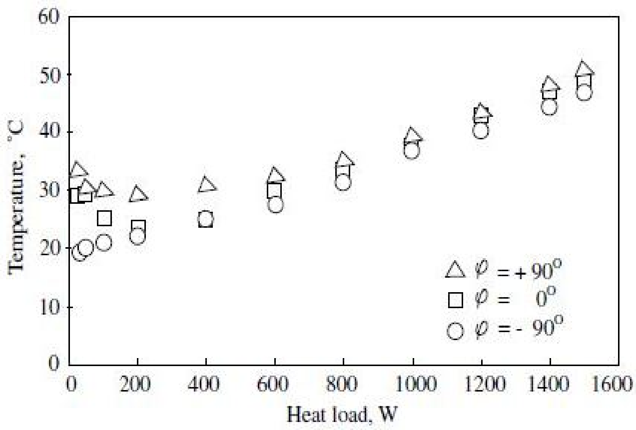

Fig.8 Evaporator temperature vs heat load (ammonia LHP 2m long)

The results of tests are presented in Fig. 8 in three different orientations as heat-load dependences of the temperature of the evaporator wall at 1-g conditions. It can be observed that in heat loads from 500 to 1500W, LHP operates with a constant conductance and the evaporator temperature at the three orientations varies only moderately. And there was no report of anomaly even at the maximum capacity achieved. It can also be seen that when the evaporator was above the condenser (+90) the temperature at evaporator wall was highest but with moons gravity being 1/6 of earths this temperature could significantly fall favoring the PV Cell. Moreover, this LHP is not the longest developed and successfully tested. Presented in [20] are the results of an ammonia LHP 5.2m long, that successfully transferred a downward heat flow from 200 to 1000W. Fig. 9[21] shows a 21 m long LHP.

Fig.9 21m long LHP

It is evident that the LHP can perform well to as much as 1600W keeping the temperature at around 45 Celsius. With the underground lunar ground almost 1 meters deep as sink which can reach as low as -53° Celsius , gravity 1/6 of earth, and with proper fin system design to reject the heat, an LHP system is likely to maintain a 1 m^2 PV Cell at excellent efficiency range with the fact that heat load will only be around 656 W at the equator. So concerning a PV Cell located at the lunar equator, either a suitable fluid has to be chosen according to a particular fixed depth so that it doesn't freeze in the condenser or a particular depth has to be chosen according to the fluid available provided that there is sufficient cooling of the PV Cell.

A possible overall system could consist of a insulated fluid container which will contain the evaporator and a conductive fluid in it. The PV cell's area will be larger than the evaporator's area of the single LHP which transfers the same amount of heat as the PV Cell produces, further the contact area for conduction would just be a line for a circular shaped evaporator, so a forced convection system could work well in this condition.

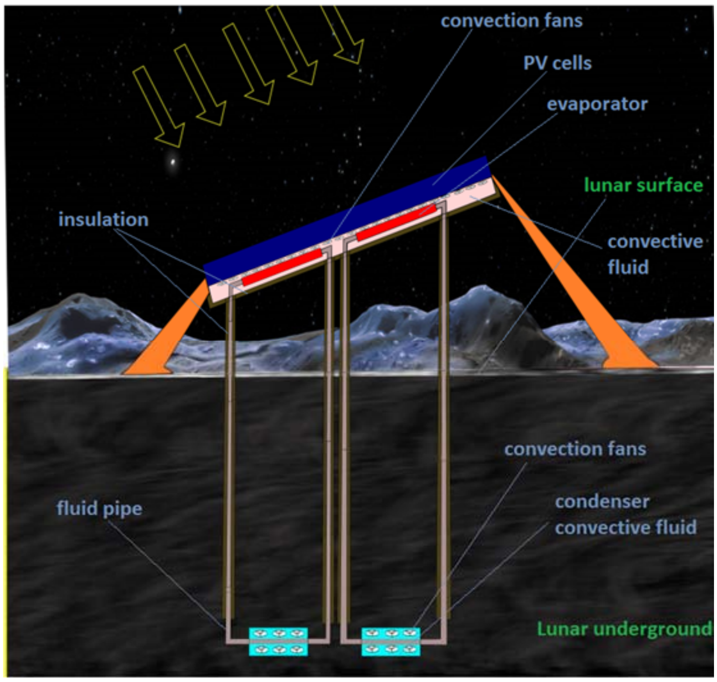

Fig. 10 Schematic of a possible lunar LHP

Small fans would need to be installed in the container to help the fluid circulate as low gravity of moon would hinder a natural buoyant circulation. Similarly, for effective heat dissipation at the condenser, the condenser will be contained within a container housing a conducting fluid in contact with the lunar ground. Likewise, small fans need to be installed. The fluid container housing the evaporator will have to be insulated so that minimum external heat influences the heat transfer process. Similarly the pipe from the evaporator to the condenser would have to be insulated till a relatively cold point in the ground has been reached as depicted in Fig. 10.

5. Conclusion

In spite of the harsh working temperatures, the hidden features like cold underground layers and polar craters of moon could as well provide a suitable heat sink. With temperatures reaching around -53° to -203° Celsius just a passive cooling method could perform well enough to keep the PV cell operating near to maximum efficiency conditions in contrast to active methods which would require power. And, LHP could be the best passive system to experiment with because of its favorable working temperature ranges, heat carrying capacity up to large distances and its successful applications. The evaporator and the pipes would have to be insulated from external heat flux such as surface radiation and fans included to allow proper convection. But then again, for developing and finding out the feasibility of a system in an alien environment to earth would require immense experimentations with creating an environment same as the moon's. Moreover, this paper only address one issue, the overall PV system will be bombarded with various other factors like lunar dust, radiative heat transfer from surface, affect of freezing temperature during lunar night, solar proton events and other factors which could yet have to be discovered.

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