Efficiently mining near and within a lunar permanently shadowed region (PSR)
(Directed sunlight segment)

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(NOTE: As will be shown, in order to see some benefit from the solutions proposed herein, no changes are required to the means, output, or location of the NASA solar-powered power plant (SPP).)

Collimated/reflected sunlight apparatus (CSA)

The use of a CSA is proposed herein. For thermal applications, CSA's can greatly increase the amount of useful work per area of intercepted solar insolation. A CSA can also decrease the overall mass required on the lunar surface per unit of extracted products. Finally, CSA's easily lend themselves to the use of laser beams as means for transferring electrical and/or thermal energy between one Laser Power Node (LPN) and another, including LPN's located on O2 and H2O extraction plants and MP's. LPN's increase the efficiency and decrease the overall mass of equipment operating on the lunar surface, especially when used in conjunction with CSA's.

(NOTE: Directed energy in the form of an LDPN has been addressed in a separate segment of this proposal).)

NASA Watts on the Moon Challenge (NASA Challenge)

The NASA Challenge asked how best to (a) store and (b) distribute electrical energy to (1) an oxygen (O2) extraction plant, (2) a water (H2O) extraction plant, and (3) a "mobility platform" (MP), using only the electrical output of a proximately located SPP, which itself is proximately located on the rim of a crater with specifically-defined solar insolation access and PSR's. For the two extraction plants, solar thermal energy at the power plant is converted into electricity, stored and/or transported to the two plants, and then partially converted back into thermal energy. A percentage of the generated, stored and/or transported electricity will also be used to provide motive force for the MP and for other uses where electric energy is required, such as pumps, compressors, drives, sensors, etcetera.

Shackleton Crater (SC)

SC is a unique lunar crater, a portion of the rim of which lies almost exactly on the lunar south pole. Less than a handful of peaks on the rim of SC constitute some of the very few points on the lunar surface where summits exist that meet the specifically defined solar insolation limitations set forth by the NASA Challenge.

Therefore, this proposal will use a hypothetical peak on SC as representative of the NASA Challenge characteristics. Designing for that hypothetical peak will thus automatically ensure that design elements will fall within many of the NASA Challenge guidelines.

Inherent NASA Challenge limitation

Inherently, a conversion from solar thermal energy to electricity and back to thermal energy will incur very large losses, on the order of 60 to 80 percent or more, relative to the captured solar thermal insolation. However, to great extent for both extraction plants, it is possible for direct thermal energy to be utilized in place of electrical energy. Upon analysis, it appears likely that, due to the ability to easily and efficiently store and transfer electrical energy for later use, the requirement for continuous operation of the O2 plant informed the choice of electricity as the total means of supplying energy input and the exclusion of any use of direct thermal energy.

Further, it has become clear that the driver for the very limited choices set forth for the location of the NASA Challenge SPP are directly related to the requirement for the O2 plant to operate 24/7/365 once it begins extracting. By choosing a peak with defined characteristics that match one of the highest peaks on SC or other peaks on the lunar poles that approach "peaks of eternal light"[1], the NASA Challenge minimizes the required electric storage to operate the O2 plant, and thus minimizes the mass required on the lunar surface to effect that storage. This choice of driver is underlined by the fact that the energy requirements of the proposed O2 plant, which absolutely requires stored electrical energy, dwarfs the energy requirements of the proposed H2O plant.

It has also become clear that the H2O plant does not need to be handicapped by the same "real estate" requirement of the O2 plant, even for an all-electric approach, since the H2O plant is not required to operate 24/7/365. In fact, it will be shown that almost any point around the rim of SC can be the site of an adequate solar power supply for H2O plants operating within the rim of SC.

NASA Challenge all-electric approach

The proposed NASA power plant provides **10 kW** electrical power (kWe) at 120VDC. Irregular periods of solar illumination and eclipse occur over the course of a 709-hour (i.e, 1 Earth-month) lunar diurnal cycle. The plant location was selected to ensure that "the initial illuminated period in each diurnal cycle is at least 300 hours long." The remaining illuminated time is "approximately split between 50% illuminated and 50% eclipsed on an irregular schedule, with no eclipsed period longer than 30 hours and all illuminated periods at least 20 hours long". Thus, the hours split 50/50 equal 409, which means 204.5 split/hours are illuminated, yielding a total of 504.5 total illuminated hours. At 10 kWe, total generated power equals **5,045 kWh** electrical per lunar diurnal cycle (LDC).

Per a 2009 NASA study[2], photovoltaic conversion of solar energy would yield about 21% solar-to-electric efficiency. (Note: For the purposes of this analysis, a solar-powered CIGS PV array (see 2009 NASA study slide 44) will be presumed, with an overall conversion efficiency of 21%. However, this could be increased to over 30% with

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[1] https://en.wikipedia.org/wiki/Peak_of_eternal_light

[2] https://www.nasa.gov/pdf/315858main_Cheng-yi_Lu.pdf

the alternative of solar thermal conversion via a primary closed cycle heat engine[3], and potentially more with the possibility of using the PSR itself for cooling said heat engine.) Thus, to output 10 kWe, solar insolation would equal **47.6 kW** per LDC, or **25,015 kWh** total solar insolation per LDC. Using 1.4 kW/m2 as the solar insolation available on the lunar surface, the area of the solar receiver would thus equal **34 m2**.

(Note: Because the sun is perennially just above the lunar horizon on the rim of SC due to an axial tilt relative to the solar plane of about 1.5°, the solar receiver array will need to be erected essentially perpendicular to the lunar surface, and the sun must be tracked throughout a 360° rotation over the lunar diurnal cycle. Using the data on 2009 NASA study slide 44, the mass of the solar array might equal 0.82 kg/25 W, or 1,904 kg. That mass does not include the frame for holding up the array or the mechanism for continually rotating the array towards the sun, which would probably at least double the required mass, even on the lunar surface. The array system would also need to be mounted on the top of the SC peak, adding considerably more mass, not to mention additional mass requirements resulting from the potential complexity of construction at that location.)

Requirements for powering the O2 plant

To avoid damage from thermal cycling of high temperature components, the O2 production plant must produce O2 continuously over the full 709-hour lunar diurnal cycle. The plant is located 100 m from the power plant, and extracts O2 continuously at a rate of 1 kg/hour from dry regolith that is 14% O2 by mass (average specific heat of regolith is 1.2 kJ/kg-°C). O2 extraction requires heating regolith from 200°C to 1,800°C. The plant continuously discards regolith mass at 1,100°C at a rate proportional to the O2 production rate. The O2 plant itself requires 5 kWe continuously, or **3,545 kWh** electrical per LDC. (Note for reference: During the 504.5 hours of solar insolation, or 71% of the total operation time, the required energy at the O2 plant would equal 2,520 kWh electrical per LDC.)

Requirements for powering the H2O plant

The stationary H2O plant is located inside the PSR, about one (1) km from the power plant on the crater rim. Icy regolith is brought to the H2O plant by the MP. The icy regolith is 2% ice mass fraction and 98% dry regolith. The icy regolith is heated from -220°C to +200°C to fully extract the H2O. The plant produces 10 kg of H2O during a 100-hour operating cycle. Dry regolith at 150°C is continuously discarded. Due to issues related to long-term exposure to the severe cold environment in the crater, a continuous thermal protection load of 0.2 kW thermal (kWt) delivered at 50°C is required to maintain an operable environment for the plant components. During production of H2O inside the crater, electric power is required in repeated one-hour cycles of 1⁄2 hour

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[3] https://web.archive.org/web/20130219193847/https://share.sandia.gov/news/resources/releases/2008/solargrid.html

at 0.5 kWe followed by 1⁄2 hour at 1 kWe, or an average use per hour of 0.75 kWe. Total mission activity duration is up to 300 hours. Total required electric energy for H2O generation is **225 kWh** electrical per LDC. Assuming waste heat from H2O production is sufficient for thermal protection during the 300 hour operating cycle, total thermal protection load requirement over the 409-hour non-operating cycle is **82 kWh** electrical per LDC. Therefore, total required electric energy for the H2O plant operation is **307 kWh** electrical per LDC. At a solar conversion efficiency of 21%, total required solar insolation equals **1,462 kWh** per LDC.

Requirements for powering the MP

Per the NASA Challenge, the mission of the MP is collecting and delivering water-bearing material to the H2O plant for a minimum of 100 hours. Total mission activity time may not exceed 200 hours. Descent of the MP into and out of the crater is not required, but would consist of a 10-hour trip descent and a 10-hour descent with a continuous 0.15 kWe load for vehicle mobility. The MP will have an additional 0.005 kWe load for every additional 1 kg of payload. Inside the crater, MP electric power is required in repeated one-hour cycles of 1⁄2 hour at 0.1 kWe followed by 1⁄2 hour at 0.2 kWe, or an average use per hour of 0.15 kWe. Inside the crater, the MP components require 0.05 kWt continuously to maintain an operable environment. During any time outside the crater, the MP will require continuous 0.05 kWe to operate, but no thermal protection power.

- Calculation of MP use outside the crater is considered out of scope for this NASA Challenge.
- Since no thermal protection is required outside the crater rim, and the total non-H2O plant operating time per LDC equals 609 hours, 20 hours travel time out of the crater will be added to the travel time of the MP, totaling to 120 hours travel time. This will avoid thermal protection equal to 30.5 kWh per LDC.
- If 30 kg of H2O will be generated per LDC, 1,500 kg of lunar regolith be transported.
- Assuming the MP can travel 1 km in 10 hours, it will travel 10 km in 100 hours.
- It is assumed the MP travels 5 km when hauling/dumping regolith, and 5 km when empty/picking up regolith
- Empty/picking up travel plus thermal protection equals an average of **0.2 kWe**..
- It is assumed the MP on average travels 1 km per round trip, or a total of 10 round trips. The MP thus carries 150 kg per regolith hauling trip, and regolith hauling adds 0.75 kWe peak power demand per round trip. Total peak power demand thus equals **0.95 kWe**.
- Travel with regolith will require **47.5 kWh** electrical per LDC.
- Travel without regolith will require **14 kWh** electrical per LDC.
- Since the MP is traveling out of the crater, it can carry the extracted H2O out of the crater. Assuming the 20 hours ascending/descending travel time includes 10

hours empty and 10 hours with 30 kg H2O, ascending/descending will require an additional **0.15 kWh** per LDC H2O hauling energy (not including packaging).

Total MP power demand per LDC therefore equals **~62 kWh** electrical per LDC. At a solar conversion efficiency of 21%, total required solar insolation equals **295 kWh** per LDC.

(Note: the H2O plant is assumed to operate for 300 hours, while the MP will only service the H2O plant for 100 hours. Thus, the first round trip from and back to the rim of the crater, the MP cannot "wait" at the H2O plant for a delivery of H2O. Thereafter, however, it can pick up the already-extracted delivery.)

Summary of NASA Challenge electrical requirements

- Total H2O plant and MP electricity requirements equal **369 kWh** electrical per LDC. At a solar conversion efficiency of 21%, total required solar insolation equals **1,757 kWh** per LDC. Note that the H2O plant and MP electrical requirements are thus 9.6% of the O2 plant.
- Total O2 plant, H2O plant, and MP electricity requirements: **3,914 kWh** electrical per LDC. That equals 78% of the total power output of the SPP. Note that these calculated power requirements do not include thermal, electrical, or other operating losses, the use of an MP for gathering regolith for the O2 plant, or other electrical requirements

CSA-powered O2 plant

For the purposes of this proposal, it is assumed that all reflectors would have a reflecting efficiency of 93% and all lenses would have a refracting efficiency of 98%.

During periods of solar insolation, a more efficient approach to reaching the peak temperatures required by the O2 plant would be to divert the solar beam to the O2 plant by simple reflection, as in the solar power tower concept (https://en.wikipedia.org/wiki/Ivanpah_Solar_Power_Facility) or the solar furnace concept (https://en.wikipedia.org/wiki/Odeillo_solar_furnace & https://en.wikipedia.org/wiki/Solar_furnace_of_Uzbekistan). Unfortunately, because the sun is perennially just barely above the lunar horizon on the rim of SC, the sun must be tracked throughout a 360° circle over the lunar diurnal cycle. As a result, neither a conventional solar power tower nor a conventional solar furnace design can be used very effectively.

However, construction of what might be termed a "hybrid" solar furnace is possible. It is proposed that, as a means of meaningfully increasing operational efficiency while simultaneously decreasing overall system mass, a solar reflecting system (for example, a system resembling those described herein) be mounted contiguous to the NASA Challenge solar-powered generator.

Single reflector CSA and O2 plant

For the single reflector CSA, it is important that the O2 plant concentrator is at a substantially lower altitude than the reflecting mirror, thus creating a significant downward angle between the center of the reflector and the center of the concentrator.

Since information concerning the actual relative altitude of the O2 plant and the solar power plant is unknown, an analysis of this approach will be conducted that assumes the O2 plant would in fact be located at a sufficiently lower altitude. If such is not the case, a double-reflector system will have to be used (see below).

When the O2 plant is directly between the sun and the reflecting mirror, the mirror reflects at the most acute angle possible. Conversely, when the reflecting mirror is directly between the O2 plant and the sun, the mirror reflects at the most obtuse angle possible. Thus, as the reflecting mirror rotates to track the sun, the “angle of incidence” will vary between these two angles. Since the O2 plant is presumed to be stationary, the vertical angle between the center of the concentrating mirror and the center of the reflecting mirror can be set. However, because of the 1.5 degree tilt of the lunar axis, the sun will both rotate around the lunar pole and will rise and fall on the lunar horizon. As a result, the reflecting mirror will need to be tilted in 3 axes around its center point. The precise nature of the angle of incidence will thus depend at any given time on the changing three dimensional plane between the center of the sun, the center of the reflecting mirror and the center of the concentrating mirror. (Note: as will be shown, there is a second purpose for the main reflecting mirror.)

During the 504.5 hours of solar insolation, the required energy at the O2 plant would equal 5 kW, and the assumption made for this analysis is that, when solar insolation is available, the required energy to extract O2 from regolith can be purely thermal, or 5 kWt. Total required energy during the interval when solar insolation is available is thus equal to **2,520 kWh** thermal per LDC. Assuming a reflecting mirror and concentrating mirror system with 93% reflecting efficiency, solar beam transfer efficiency would equal 86%. Delivering 5 kWt would thus require solar insolation of **5.81 kWt** or **2,931 kWh** thermal per LDC, or a reflected solar beam area of **4.15 m2**, or about **2.30 m** in diameter. As noted above, over 100 m that beam will diverge 0.93 m, requiring a concentrator **3.23 m** in diameter, or **8.2 m2**.

The additional power required over 204.5 hours would equal, at 5 kWe input, **1023 kWh** electric per LDC, or 5 kWe, or **3.6 m2** at 21% conversion efficiency, or a circular array 2.2 m in diameter. This would be would be supplied by the NASA power plant.

In relation to the NASA Challenge SPP’s calculated O2 plant power requirement of **3,545 kWh** electrical per LDC, an upscaled plant would theoretically produce **3.5x** more O2 using **1.46x** more solar insolation.

Double reflector CSA and O2 plant

In this approach, the NASA-proposed solar electric generator on top of the crater rim’s peak would be replaced by the combination of a single reflecting mirror and a fixed re-reflecting mirror. In the double reflector system, the main reflecting mirror always directs the solar beam to the fixed mirror located either above or below the main reflecting mirror.

One advantage over the single reflecting system is that only two axes of movement are required by the main reflecting mirror, which turns continually through 360° along one axis to face the sun and adjusts in a second axis to account for seasonal changes in the height of the sun on the lunar polar horizon. (Note: as will be shown, there is a second purpose for the main reflecting mirror.) Another advantage is that the O2 plant concentrator can be above, at a level with, or below the fixed mirror. The disadvantage is that two reflectors are required, reducing the overall reflecting efficiency.

Assuming a reflecting mirror, a re-reflecting mirror, and concentrating mirror system, and assuming reflectivity efficiency equals 93 %, solar beam transfer efficiency could ideally equal 80%. Delivering 5 kWt would thus require solar insolation of **6.25** kWt or **3,153 kWh** thermal per LDC, and a reflected solar beam area of **4.46 m2**, or **2.38 m** in diameter. As noted above, over 100 m that beam will diverge 0.93 m, requiring a concentrator (2.38+0.93=) **3.3 m** in diameter, (**8.6 m2**).

In relation to the NASA Challenge power plant's calculated O2 plant power requirement, an upscaled O2 plant would theoretically produce **3.5x** more O2 using **1.9%** more solar insolation.

CSA-powered combined H2O plant and MP

For the H2O plant solution, the MP is considered part of the H2O plant, since it is essential for its operation, and since, as will be shown, it is not necessarily located near the O2 plant. Shown below is a single reflector system analysis. A double reflector system analysis would be similar to that conducted above for the O2 plant.

Per the NASA Challenge specifications, the H2O plant is 10x farther away and on the opposite side of the rim from the O2 plant, or 1 km down in the crater of the PSR. Also unlike the O2 plant, per the NASA Challenge specifications, the H2O plant only requires power for 300 hours per LDC. Lastly, unlike the O2 plant, the majority of the required energy is low temperature (~200°C) thermal energy. Thus, while the proposed solution of using reflected solar thermal energy remains in common, optimizing that energy usage constitutes a major difference between the two power plants.

As will be shown, for the H2O plant solution, the total required thermal and electrical needs of the H2O plant and the MP can be totally supplied by reflected solar insolation. Assuming a heat engine like a stirling engine is used[4], and considering the extreme cold available for cooling the heat engine, 35%+ thermal efficiency is easily possible, leaving 65% of the input solar energy as waste heat. A 35/65 balance of electrical and thermal energy should be sufficient to approximate the same overall energy balance of a strictly electric approach.

For the two power plants:

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[4] https://web.archive.org/web/20130219193847/https://share.sandia.gov/news/resources/releases/2008/solargrid.html

1. Energy storage for the H2O plant is mostly important for thermal protection purposes. However, energy storage or some alternative is essential for the MP.
2. In terms of access to solar insolation, 300 hours of solar insolation is much less stringent than 504.5 hours. Consequently, there are few locations across the rims of craters on the north and south lunar poles, or indeed over most of the lunar surface, that do not have access to 300 hours of solar insolation per LDC. As a result, the proposed NASA Challenge water production facility does not need to be directly tied to the O2 production facility. The only cost of working farther away is the cost of transporting the H2O a longer distance, which would be a minor cost.
3. Unlike the O2 plant, the H2O plant can use thermal energy to generate electric energy first, and use waste heat from the electric generation process to power the extraction of H2O.

It will be assumed that 100% of the energy required by the H2O plant to extract H2O from the regolith can be thermal energy. Other than 82 kWh electrical per LDC for thermal protection, the total energy required for extracting H2O therefore equals **225 kWh** per LDC. The total solar insolation required for a 65% waste heat stream thus equals **346 kWh** per LDC.

As calculated above, the MP will require **62 kWh** electrical per LDC to perform its operations. An additional 82 kWh electrical per LDC is required for H2O plant thermal protection, for a total of **144 kWh** electrical per LDC. For a 35% efficient heat engine, total required solar insolation to produce 144 kWh electrical per LDC would equal **411 kWh** and waste heat would equal **267 kWh** per LDC.

However, if 225 kWh per LDC can extract H2O from 1,500 kg of regolith, then 267 kWh per LDC can extract 19% more regolith, or an additional 280 kg. That will cost an additional 1.4 kWe, bringing the total to 4012.4 kWh. However, it also increases the extracted H2O by 19% to 35.7 kg.

Total solar insolation of 412.4 kWh over 300 hours of solar insolation equals a required solar input for the H2O plant and HP of 1.375 kWt. Assuming total reflector losses yield 0.86% transmission (single reflector), net required solar insolation equals **1.6 kW**. At 1.4 kW/m2, that would indicate a solar insolation beam area of **1.14 m2** (**1.2 m** in diameter). As noted above, over 100 m, a point beam in Earth's orbit would grow 0.93 m in diameter. Over 1,000 m, it will grow **9.3 m** in diameter, to a total beam diameter **10.5 m** and an area of **86.6 m2**.

In relation to the NASA Challenge all-electric H2O plant and MP power requirements of **369 kWh** electrical per LDC, assuming 21% solar conversion efficiency, **4.3x** more solar insolation would be required by the all-electric H2O plant than by the single-reflector-powered H2O plant and MP. Assuming 35% conversion efficiency by the NASA Challenge SPP, **2.6x** more solar isolation would be required by the all-electric

H2O plant and HP. The single-reflector-powered H2O plant will also produce 19% more H2O.

Since there is no thermal constituent, peak power demand will be comprised of the 0.95 kWe peak power demand of the MP and the H2O plant thermal protection requirement of 0.2 kWe. Total peak power demand will thus equal 1.15 kWe, indicating a stirling solar-powered engine with 1.2 kWe output capacity.

Collimating sunlight

While a 1 km distant concentrator at the H2O plant 10.5 m in diameter would be possible, it is desirable to reduce that diameter, especially if the distance is longer than 1 km. (For example, the floor of Shackleton crater is ~4.2 km deep and ~8.5 km along the 30° cone-shaped inner slope.)

Collimating a beam of light is a useful means of reducing the divergence angle of the beam. "If we collimate the output from this source using a lens with focal length f, then the result will be a beam with a radius $y_2 = \theta_1 f$ and divergence angle $\theta_2 = y_1/f$. Note that, no matter what lens is used, the beam radius and beam divergence have a reciprocal relation. For example, to improve the collimation by a factor of two, you need to increase the beam diameter by a factor of two."[5]

What are the losses associated with collimating? There are basically two ways to collimate a beam: Reflection from a mirrored surface, and refraction through a lens. As spoken of above, refraction is more efficient than reflection, but sunlight creates an issue for refraction, with multiple wavelengths refracting at different angles. (That's not a problem for laser light, which is typically a single light wavelength.) Reflecting, on the other hand, generally involves higher thermal losses.

As stated above, over 100 m, a point beam in Earth's orbit would grow 0.93 m in diameter, or 0.0093 m/m. For a 3x collimating process, that diversion is reduced to 0.0031m/m. Over 1 km, a 3x collimated solar point beam would therefore diverge **3.1 m** For a 1.6 m diameter solar beam, the collimated beam diameter would equal **4.8 m**. Over 1 km, a 3x collimated solar point beam would diverge to the sum of the point beam divergence and the original solar beam diameter. For a 3x collimated solar beam 4.8 m in diameter, he target concentrator diameter would therefore equal **7.9 m**, or an area of **49 m2**. That equals **57%** the area of the non-collimated system. Note that this advantage grows exponentially with the distance of reflectance. Thus, over 2 km, a 3x collimated beam will grow to **11 m** in diameter or **111 m2**, or only slightly larger than the non-collimated beam at 1 km distance. A **1.2 m** reflected solar beam without collimation will grow over 2 km to **19.8** m in diameter or **308 m2**. And so on.

Assuming reflecting is used throughout, a minimum of four reflecting surfaces will be required; (1) the main reflector that reflects the moving solar beam towards the distant concentrator, (2) the diverging mirror that increases the beam diameter, (3) the

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[5] http://www.newport.com/Focusing-and-Collimating/141191/1033/content.aspx

collimating reflector, and (4) the target's concentrator mirror. If a 93% reflectivity efficiency is assumed, that will create a reduction in solar insolation to 75% of the original insolation. Thus, for each m2 of reflected solar beam, the solar beam cross section area would need to be 1.33x larger. For the 1.2 m diameter beam required for the H2O plant and MP, the required solar beam diameter would therefore increase to **1.6 m** or **2 m2**, and the required solar insolation would increase to **2.8 kW**. Over 300 hours, total required solar insolation would equal **840 kWh** per LDC.

In relation to the NASA Challenge all-electric H2O plant and MP power requirements of **369 kWh** electrical per LDC, assuming 21% solar conversion efficiency, **2.1x** more solar insolation would be required by the all-electric H2O plant than by the double-reflector-powered H2O plant and MP. Assuming 35% conversion efficiency by the NASA Challenge SPP, **1.25x** more solar isolation would be required by the all-electric H2O plant and HP. The double-reflector-powered H2O plant will also produce 19% more H2O.

Aggressively Collimating Technology (ACT) thin film lenses

An alternative to the use of reflecting mirrors is the use of refracting lenses. A refracting lens can be useful for two reasons: (1) It can reduce reflecting losses; and (2) it can reduce overall mass, especially for systems that require tracking capability. ACT is also being proposed within the NASA Challenge as helping enable a solution to the issues of energy storage and transfer[6].

Originally, the ACT concept envisioned the use of thin film lenses as a means for substantially reducing the mass of lenses used in space. In their application here, ACT lenses would be used principally to increase the efficiency of radiant energy transfer. In some cases, a moderate decrease in mass in comparison to reflectors is likely.

However, there is a potential issue with lenses, including thin film lenses, when used with solar radiant energy, and that is the development of wavelength refraction. The sun's light has within it many wavelengths, and it is well known that light, passing through a transparent medium at an angle, will refract into its constituent wavelengths. This can be an issue depending on the application, and specifically depending on the length of travel that the refracted solar light has to travel.

One possible application to CSA's where diffracted sunlight is not likely to be an issue is in the use of concentrators. ACT lenses are applicable to processes that concentrate sunlight on a target. And since the CSA target proposed herein is a concentrator with a very large area, it is reasonable to infer that, not only would ACT lenses allow the efficiency of concentration to be increased, but would also permit a reduction in mass.

The applicability to collimating sunlight over a longer distance may also be possible, depending on the distance the light must travel. However, there appears to be

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[6] Efficiently mining near and within lunar PSR'S (Distributed Nodes)

little research, if any, on the practicality of refractively collimating sunlight over larger distances. An exploration of this potential is part of the research being proposed here.

SC and rim-mounted LDPNs

Because SC is located on top of a lunar massif, because SC is very close to the lunar south pole, and because the Moon is nearly aligned with the Sun/Earth plane of rotation, the sun is visible for at least half a lunar diurnal cycle from many spots on the rim. Consequently, at many locations, one side of SC receives sunlight when the opposite side does not. As a result, during times when solar insolation is not available to the SSP and CSAs, a solar powered laser beam can be fired across SC's 21 km diameter, essentially replacing the sun's insolation with a like amount of laser energy, thus removing the requirement for energy storage of any kind other than for emergency backup power.

The O2 plant is the only plant that needs to receive 24/7/365 input. For an O2 plant receiving 5 kWe:

- Over 709 hours, total equals 3,545 kWe, or at 21% efficiency, **16,881 kWh** of solar insolation.
- With CSA & 86% solar beam transfer efficiency, solar thermal insolation requirement equals **2,931 kWh** thermal per LDC.
- At 5 kWe, **1,023 kWh** electric per LDC would be supplied by the NASA power plant during non-solar portion*.
- Laser energy to photo-voltaic cells received at 50% conversion efficiency would require **2,046 kWh** laser insolation.
- Conversion from electric to laser at 50% efficiency would require **4092 kWh** electric at second site.
- Conversion from solar to electric at 21% efficiency would require **19,485 kWh** solar insolation at second site.

Or

- Laser energy received with 100% conversion efficiency (that is, replacing electric with pure thermal) would require **1,023 kWh** laser insolation.
- Conversion from electric to laser at 50% efficiency would require **2,046 kWh** electric at second site.
- Conversion from solar to electric at 21% efficiency would require **9,742 kWh** solar insolation at second site.

An LDPN can permit 24/7/365 mining at the proposed H2O plant, enhancing efficiency in several ways:

- A dedicated MP could stay in the vicinity of the H2O plant indefinitely, continually being productive. If the H2O plant can produce 30 kg of H2O in 300 hours, it can produce 71 kg in 709 hours. Note that, if the MP could "park" on top of the H2O plant when not in use, the requirement for extra thermal protection power drops to zero.

• A simple “cable climber” (CC) can replace the need for the MP to climb out of the crater. For a system moving 71 kg/709 hours, assuming the same rate of climb as the MP was given, or a round trip every 20 hours, the CC can run 35 round trips every lunar diurnal cycle. It would therefore only need to transfer 2 kg per round trip, which would mean the cable system could be extremely light weight, especially if the CC were electrically powered by a “tuned” laser-voltaic system. In addition, the CC would only need to be powered climbing. Lunar gravity could easily return it to the H2O plant.

• The CC and the MP could be powered by a laser mounted on the H2O plant. Alternatively, in the case of a laser beam already being directed at the H2O plant, use laser deflectors to deflect laser beams to the CC and the MP. Note that waste heat from the laser photovoltaic array could be used to supply thermal protection to the CC or MP. Also, if the laser were on the H2O plant, the 50% waste heat from powering the laser could be used to increase H2O production. Note that a laser can power “tuned” photocells that can potentially reach very high conversion efficiencies (50-80%).

• For power broadcast over longer distances than a few kilometer, power can be beamed by two LDPN’s located on either side of SC depending on where solar insolation is available. All energy sent in this manner can be utilized either by converting it into electrical energy at high efficiency, by using the laser output as direct thermal energy, or by splitting the main beam into smaller beams and diverting them to directly power the MP and the CC.

Finally, note that the H2O plant itself could be suspended by cabling from the rim, and might thus be able to both ascend and descend SC’s inner cone. The H2O plant would simply travel “over” the portion of regolith that contained frozen H2O, melting out the H2O as it travelled. The presence of a high powered laser might be very useful in clearing a path for the H2O plants.

If there were two H2O plants, their masses could counterbalance one another. One could be lowered while the other were raised. In that instance, there might be very little requirement for an MP as a separate piece of machinery. The CC would travel along the cable that raises or lowers the H2O plants. In such an instance, it would be best for the mining plant to start at the bottom of the cone and work its way up, dropping used regolith onto a surface that had already been mined.

The PLDPN

As proposed above, a SRS, TRS, or RCS can be used to reflect sunlight into a PSR, efficiently broadcasting energy wirelessly into a region of deep shadow and extreme cold. It is also possible to use that energy to power a closed-cycle heat engine, such as a “stirling" engine. Stirling Cycle engines are thermal engines of exceptional efficiency (https://web.archive.org/web/20130219193847/https://share.sandia.gov/news/resources/releases/2008/solargrid.html). The Carnot efficiency of closed cycle thermal engines is entirely dependent on the temperature of the thermal source and the temperature of the thermal sink, as succinctly described by the well-know Carnot equation that defines theoretical efficiency of any thermal engine as equal to the temperature of the source (T1) minus the temperature of the sink (T2) divided by the temperature of the source, or (T1-T2)/T1. Clearly, any heat engine operating in the region of the PSR is highly advantaged. Actual thermal efficiency of a heat engine in a PSR could reach 40% or even higher.

Use of an SRS, TRS, or RCS essentially makes high temperature thermal energy available inside a PSR. In the case of an SRS using an ACT concentrating lens, if the efficiency of such a heat engine were in the realm of 40%, the solar transfer efficiency of the SRS were 93%, and the solar transfer efficiency of the ACT lens were 98%, then the overall conversion of solar insolation into work would equal 36.5%. (Note that other configurations would give different results.) If the work thus produced then powered a DPN, it would be advantaged over a DPN outside of a SRS in two ways: First, as stated above, it would be advantaged in efficiency of conversion per area of solar insolation. Second, it would be advantaged due to the ability to use conduction for radiating away the exhausted thermal energy. Note that, on the lunar surface and in direct sunlight, with no atmosphere available for cooling purposes, the only practical way to radiate away exhausted thermal energy is black body radiation, which is a mass-intensive process, and thus not preferable.

It is also possible to create an artificial PSR. That is, it is possible to create an area that is artificially shaded from sunlight. That would be simplest and most effective in close proximity to a PSR, in areas which are blocked from sunlight appreciably longer than they see sunlight, such as the area just below the rim of Shackleton Crater. In Shackleton Crater, due to the nature of the sunlight striking at a very shallow angle on the opposite rim, any area within the rim of Shackleton by definition will see appreciably less sunlight per lunar diurnal cycle than over most of the lunar surface. Erecting a permanent shade above an area that sees shade longer, such as just below the rim of Shackleton Crater, means that area will maintain a lower temperature longer. Note that a very thin reflective film can be used for construction of a shade, and thus require very little mass.

The elements comprising a PLDPN are:

1. A solar reflector such as an SRS, TRS, or RCS.
2. A PSR, either natural, artificial, or a combination of both.
3. A heat engine.
4. An electric generator.
5. 5. A distribution system, such as a CDPN, MDPN, LDPN, or CHDPN.

The CHDPN

On December 28, 1965, US Patent #3225538 was granted to R. B. Bland. It is entitled “Conversion of heats of Chemical Reactions to Sensible Energy”. (A related patent was granted on December 11, 1962 to R. B. Bland Et Al entitled “Cooling with Endothermic Chemical Reactions”.) In February, 1978, a final report was issued under

ERDA Contract EU=76-C-02-2676 entitled “Closed Loop Chemical Systems for Energy Storage and Transmission (Chemical Heat Pipe)”, prepared by General Electric Company for the US Department of Energy.

The processes disclosed within the 1965 patent and the ERDA Contract propose the development of a system for storing and transferring thermal energy in a chemical form. It is here proposed that these processes be applied to the efficient transfer of thermal energy from point to point on the lunar surface.

One application on the lunar surface for these processes would be to take otherwise-waste thermal energy from an oxygen-extraction plant located outside a PSR and pump it via a Chemical Heat Pipe to a water-extraction plant inside a PSR.