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Thermal Energy for Lunar In Situ Resource Utilization: Technical Challenges and Technology Opportunities

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Abstract

Oxygen production from lunar raw materials is critical for sustaining a manned lunar base but is very power intensive. Solar concentrators are a well-developed technology for harnessing the Sun’s energy to heat regolith to high temperatures (over 1375 K). The high temperature and potential material incompatibilities present numerous technical challenges. This study compares and contrasts different solar concentrator designs that have been developed, such as Cassegrains, offset parabolas, compound parabolic concentrators, and secondary concentrators. Differences between concentrators made from lenses and mirrors, and between rigid and flexible concentrators are also discussed. Possible substrate elements for a rigid mirror concentrator are selected and then compared, using the following (target) criteria: (low) coefficient of thermal expansion, (high) modulus of elasticity, and (low) density. Several potential lunar locations for solar concentrators are compared; environmental and processing-related challenges related to dust and optical surfaces are addressed. This brief technology survey examines various sources of thermal energy that can be utilized for materials processing on the lunar surface. These include heat from nuclear or electric sources and solar concentrators. Options for collecting and transporting thermal energy to processing reactors for each source are examined. Overall system requirements for each thermal source are compared; system limitations, such as maximum achievable temperature are discussed.

Nomenclature

A_{conc}	concentrator solar collector area
A_{spot}	spot size
CR	concentration ratio
$CR_{\mathrm{max,CPC}}$	maximum concentration ratio of a dielectric compound parabolic concentrator (CPC)
$CR_{\mathrm{2Dmax},Th}$	maximum concentration ratio of a line-based trough concentrator
$CR_{\mathrm{3Dmax},Th}$	maximum concentration ratio bounded by thermo-dynamic limit of solar concentration
I_{Sun}	intensity of Sun
L_o	initial length

ΔL	change in length
n	index of refraction of dielectric (lens) material
n_{surr}	index of refraction of surroundings
P_{conc}	collected solar power
T_{spot}	temperature of spot
T_{∞}	ambient temperature
ΔT	change in temperature
α	coefficient of thermal expansion
ε	(regolith) emissivity
θ_{max}	acceptance angle of CPC
θ_{Sun}	Sun's divergent half-angle
η_{conc}	concentrator efficiency
σ	Stefan-Boltzmann constant ($5.6704 \cdot 10^{-8}$ Wm^{-2}K^{-4})

Background

Solar concentrators use optical media, such as lenses and mirrors, to focus incident (solar) light. Concentrated light can then be focused to produce thermal or electrical energy via photovoltaic (PV) cells. Solar concentrator technologies date back to Leonardo da Vinci, who suggested making a parabolic mirror four miles across in 1515 as a means of melting metals for industrial processes (Ref. 1). Solar concentrators have been applied in industry, consumer products, and numerous advanced technologies. Concentrator technologies have applications across the electromagnetic (EM) spectrum; paraboloid shaped antennae dishes used for satellite communications use similar geometries for radio waves that mirror-based concentrators use for visible light. Parabolic trough technologies are applied for cutting-edge terrestrial solar power plants and in space via a Stretched-Lens Array (SLA) Fresnel concentrator design (Ref. 2). Concentrator technologies enable a higher mass-specific power rating than planar PV; the promise of higher efficiencies and higher power output for lower mass and cost are enticing goals continually spurring further technological developments.

Introduction to Solar Concentrators

A solar concentrator collects radiation and concentrates energy into a reduced spot of light. This concentrated sunlight can be used to heat up materials, such as lunar regolith. Surface temperature of material at the spot of concentrated sunlight is governed by an energy balance between power flux, density of concentrated sunlight and losses to the surroundings. Heat losses will be a combination of:

- Conduction to surrounding solid material(s)
- Convection to the atmosphere or other fluids
- Radiation to the surroundings.

If the material is in a vacuum, such as on the lunar surface and has a low thermal conductivity, as does lunar regolith, then conduction and convection methods of heat transfer can be ignored. Radiative heat transfer, as expressed by the Stefan-Boltzmann Law (given in Eq. (1)) will determine the ultimate achievable material temperature within an illuminated spot.

$$P_{conc} = \sigma \varepsilon A_{\mathrm{spot}} \left(T_{\mathrm{spot}}^4 - T_{\infty}^4 \right) \tag{1}$$

Concentrator power, P_{conc} is determined by solar intensity, I_{Sun}, assumed to be the average solar intensity of 1353 W/m^2, area of the concentrator and concentrator efficiency (Ref. 3) (η_{conc}) as given in Equation (2). For the lunar surface, temperature of the surroundings T_{∞}, is assumed to be 270 K. It should be noted that ambient temperature is wholly dependent upon lunar surroundings, and can only be calculated through a precise energy balance of the operational geography and Sun angle. Due to radiative losses of the heated material, as spot size increases there is a decrease in achievable steady state material temperature within the illuminated spot.

$$P_{conv} = \eta_{conc} A_{conc} I_{\mathrm{Sun}} \tag{2}$$

This relationship between solar flux captured by the concentrator and concentrated spot size is expressed as concentration ratio (CR) of the concentrator. It is determined by equating Equation (1) and Equation (2) and solving for the ratio of concentrator area over spot area (A_{conc}/A_{spot}). This ratio is given by Equation (3).

$$CR = \frac{\varepsilon \sigma \left(T_{\mathrm{spot}}^4 - T_{\infty}^4 \right)}{I_{\mathrm{Sun}} \eta_{conc}} \tag{3}$$

There is a theoretical upper limit on concentration ratio for sunlight. This is because the Sun is not a point source of light. The Sun's disk has a half angle of 4.653 mrad (θ_s) when viewed from Earth's distance. The theoretical limit on concentration ratio is given by one over sine squared of the solar half angle (Ref. 4), as expressed in Equation (4) (Ref. 1).

$$CR_{\mathrm{max}} = \frac{1}{\sin^2(\theta_s)} = \frac{1}{\sin^2(0.004653)} = 46{,}188 \tag{4}$$

The relation between regolith temperature within the spot of concentrated sunlight and concentrator concentration ratio at differing emissivities are displayed in Figure 1. For processing materials on the lunar surface, temperatures up to the melting point of lunar regolith are of interest. Because regolith is a mixture of materials it melts over a temperature range of 1475 to 1775 K (Refs. 5 to 7).

The corresponding CRs needed to achieve these temperatures are approximately 180 and 400 respectively. When other losses of the system are considered, such as reflectivity of mirrors, end angle losses, losses due to heat pipe or optical cable use, and deterioration of mirror performance due to lunar environmental effects, the required CR becomes much higher. Maximum CR of each concentrator is limited by overall system design as well other specific limitations that are discussed below.

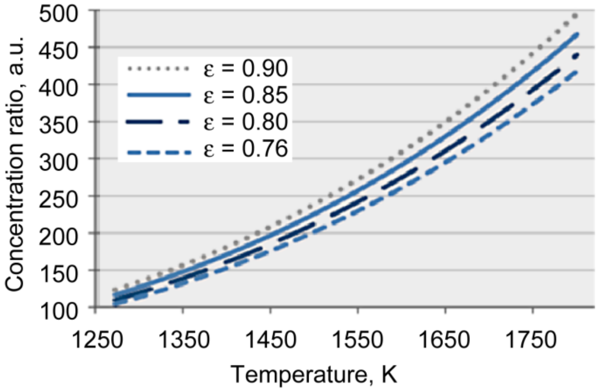


Figure 1.—Minimal Concentration Ratio versus temperature model at different emissivity levels of a solar concentrator. The sink temperature was estimated to be 270 K, but actual lunar sink temperatures are dependent on lunar energy balance. Graph only considers radiative heat transfer from surface.

While it may seem logical that a larger concentrator, capable of capturing more solar energy, can produce a higher spot temperature this is not the case because as concentrator size increases so does spot size as given by concentration ratio expressed in Equation (2). This larger spot size in turn increases heat losses to the surroundings, thereby limiting the temperature. This observation implies an important consideration about solar concentrators; a large solar flux does not mean a higher temperature. Typically, with larger concentrators, *CR*s are lower due to larger shape errors; thus, spot temperatures are less likely to result in significant oxygen production. This does not mean, however, that the aim is always to forego capturing less solar energy for a higher *CR*; a certain amount of thermal energy must be captured to reach set goals for the desired material process such as oxygen production, in this case. For example, a preliminary study previously performed determined that 15,241 W of thermal power was required to produce 1000 kg/year of oxygen from the hydrogen reduction of ilmenite (Ref. 3). It is the combination of maximum achievable temperature as well as total thermal power supplied that dictates sizing and required applicability of a concentrator design to a specific task.

Some characteristics desired in a concentrator for a lunar surface mission, such as large size, low mass, low cost and deploy-ability, tend to limit achievable concentration ratio and therefore limit process temperature. One method to enhance concentration ratio is to utilize a secondary and possibly tertiary concentrator within the system. This type of staged concentration of sunlight provides some key benefits to the concentrator system. It allows geometry tolerances of the primary concentrator to be relaxed, facilitating stowage and deployment. The secondary concentrator can then be fabricated with high precision to efficiently transport concentrated light from the primary concentrator and focus it down further to achieve the desired concentration ratio.

Another benefit of staging concentration of sunlight is that thermal energy can be redirected to the desired process location as it is being further concentrated. Utilizing a secondary and possibly a tertiary concentrator within the system can enable the primary concentrator to track the Sun while keeping concentrated sunlight focused on a specific location relative to the surface. Utilizing multiple concentrators will decrease overall system efficiency. There are losses associated with each mirror or lens within the concentrator system. These losses are due to geometry inaccuracies, light absorption and scattering. The following design features help minimize these effects:

- Short ray length, minimizes impact of mirror errors.
- For mirrors, high reflectivity, specularity and minimal geometrical errors.
- For lenses, high transmissibility, and minimal losses from groove shadowing or spectral shifting.

The Application of Concentrators to Lunar Oxygen Extraction

Concentrators have been extensively researched for In-Situ Resource Utilization (ISRU), specifically for production of oxygen from lunar regolith. Oxygen obtained from regolith could be used for extended human habitation on the Moon, rocket propellant, or for fuel cells. Lunar regolith is approximately 45 percent oxygen by weight, chemically locked up in a complex mixture of oxygen-containing minerals with balance of silicon, magnesium, calcium, and other metals. Table 1 shows major composite metal oxide compositions in lunar highland and mare regions (Ref. 6).

TABLE 1.—LUNAR SURFACE REGOLITH COMPOSITE OXIDE COMPOSITIONS

Compound	Highland (wt %)	Mare (wt %)
SiO_2	44.5	41.0
Al_2O_3	26.0	12.8
FeO	5.77	16.2
CaO	14.9	12.4
MgO	8.05	9.2
TiO_2	-------	7.3

To obtain oxygen, various materials processing methods have been developed requiring temperatures ranging from 1375 to 1875 K for extended periods of time. The limiting temperatures of this range refer to two specific processes: hydrogen reduction and carbothermal reduction processes, respectively. The carbothermal and hydrogen reduction processes are two of over 20 such processes examined for extracting lunar oxygen. The other processes are not further considered here; examples are listed below and in References 6 to 8.

- Ilmenite Reduction by Carbon Monoxide
- Ilmenite Reduction with Methane

- Glass Reduction with Hydrogen
- Reduction with Hydrogen Sulfide
- Extraction with Fluorine
- Carbochlorination
- Chlorine Plasma Reduction
- Molten Silicate Electrolysis
- Fluxed Molten Silicate Electrolysis
- Caustic Solution and Electrolysis
- Magma Partial Oxidation
- Li or Na Reduction
- Vapor Phase Reduction
- Ion (Plasma) Separation
- Plasma Reduction of Ilmenite
- HF Acid Dissolution
- H_2SO_4 Acid Dissolution
- Hydrogen/Helium/Water Production from Soil

Mirror Design Considerations

Various concentrator geometries have inherent advantages and disadvantages depending upon the application. Each design would be used for a different specific task or environment. In the following section, an overview of mirror geometry specifics, advantages and disadvantages, possible design opportunities, and design comparisons are discussed. A chart with literature values relating concentrator types and maximum *CR* is shown in Table 2 (Ref. 9 to 13).

TABLE 2.—CONCENTRATOR TYPE AND APPROXIMATE MAXIMUM CONCENTRATION RATIO (*CR*)

Concentrator type	Concentration ratio range
Fixed Cassegrain concentrator	8000 max.
Offset parabola	4000 max.
Compound parabolic concentrators (CPC)	6.5 to 10 (line-based), 81 (spot-based)
Inflatable offset	2400
Trough (line-focus)	8 to 30

Cassegrain Reflectors

A Cassegrain reflector, shown in Figure 2, is a reflecting-mirror assembly where incident solar light is focused by a collection of two or more mirrors towards a desired focus behind the primary mirror. A primary concave mirror focuses incident light in the direction of the light source; a secondary convex mirror refocuses that light towards a hole in the primary mirror, as illustrated in Figure 3 (Ref. 14). This technology is used primarily with telescopes; both the Hubble Space Telescope and its replacement, the James Webb Space Telescope, are Cassegrain assemblies (Ref. 15).

Types of Cassegrains normally differ in the shape of primary and secondary mirrors. For telescopes, which are imaging devices, mirror designs are used to counteract effects of coma, spherical, and chromatic aberrations; in most cases, the more aspheric the design and the more accurate the desired geometry, the more complex and hence, costly the manufacturing process. One possible way to for reduce cost would be to use a primary spherical mirror and an aspherical secondary mirror to correct aberrations. Researchers at Physical Sciences Incorporated (PSI) conducted simple ray-tracing analyses of two configurations; one with two spherical mirrors, and one with a spherical primary and aspherical secondary, and found that the aspherical secondary mirror sufficiently corrects spherical aberration to meet the requirements of their application (Ref. 16).

Because a Cassegrain's secondary focus can be positioned just behind the primary mirror, the ray length is usually much smaller than that of other mirror geometries of similar size. Thus, scattering effects caused by mirror aberrations are less likely to cause a decrease in spot size or lower solar flux efficiency. Rigid Cassegrains typically have the highest *CR*s of any concentrator design. However, setting up a complex array of Cassegrains, or a particularly large single Cassegrain mirror in a lunar environment, is still a complex engineering

Figure 2.—Pierce Gordon standing next to a Cassegrain concentrator manufactured for Glenn.

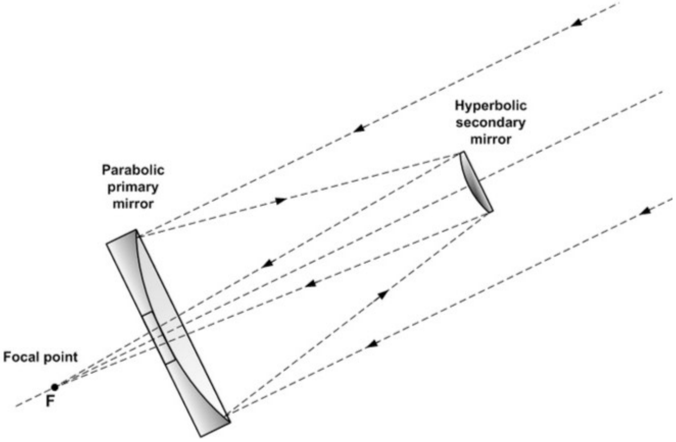


Figure 3.—Cassegrain light-ray path.

task involving a considerable design effort. A significant issue when utilizing a Cassegrain concentrator, or any geometry concentrator, for that matter, is packaging and deployment. One possible folding maneuver is the one used by the James Webb Space Telescope, where edges of the telescope fold back like leaves of a table during launch and deployment, and spread back into place during operation (Ref. 15). Other deployment possibilities can also potentially be applied and are being developed, as discussed below. Multiple concentrator units have demonstrated their utility, as demonstrated below by concentrator assemblies designed and assembled by PSI (Ref. 16).

Although theoretical performance of a Cassegrain concentrator can be very high, there are several issues with Cassegrain technology that could impact their use. They must be capable of tracking the Sun very accurately to work properly; because of its high *CR*; if the Sun’s rays were no longer parallel with the mirror’s normal, the spot could focus onto the primary mirror instead of into the mirror cavity, possibly causing catastrophic mirror damage.

Most Cassegrain designs also have supports that hold the secondary mirror in place blocking some solar energy from reaching the first mirror; thus the entire mirror is not used to its full potential. Because Cassegrains have two mirrors, they have two sources of reflectivity loss. Deterioration of coatings within the lunar environment must also be considered. Because the Cassegrain’s focus moves along with the tracking mirror, a process is needed to transfer solar energy to the stationary reactor; each energy transfer option has inherent heat losses. As with most concentrator designs, Cassegrain technologies can be assembled in modular fashion thereby enabling them to be effectively utilized for most lunar environments.

Offset Parabola

Circles create a slight aberration of light rays at the focus; the best geometry for focusing parallel light rays is in fact, a parabola. Though the Sun’s rays diverge at a small angle, and some concentrators do account for such aberration, parabolic geometries are sufficient approximations for optimum focusing technology. Parallel light rays converge at the parabola’s focus. In fact, most advanced non-imaging optics technologies utilize a parabola as the cornerstone of the geometrical design. The offset parabola configuration is a reflecting mirror whose shape represents a portion of a whole paraboloid. If the Cassegrain primary mirror is a paraboloid located at the center, an offset parabola is a portion of the paraboloid’s sidewall, as seen in Figure 4 and Figure 5 (Ref. 17).

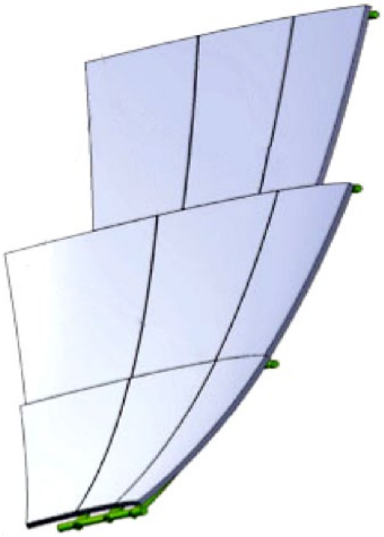


Figure 4.—Concentrator with off-set parabolic geometry.

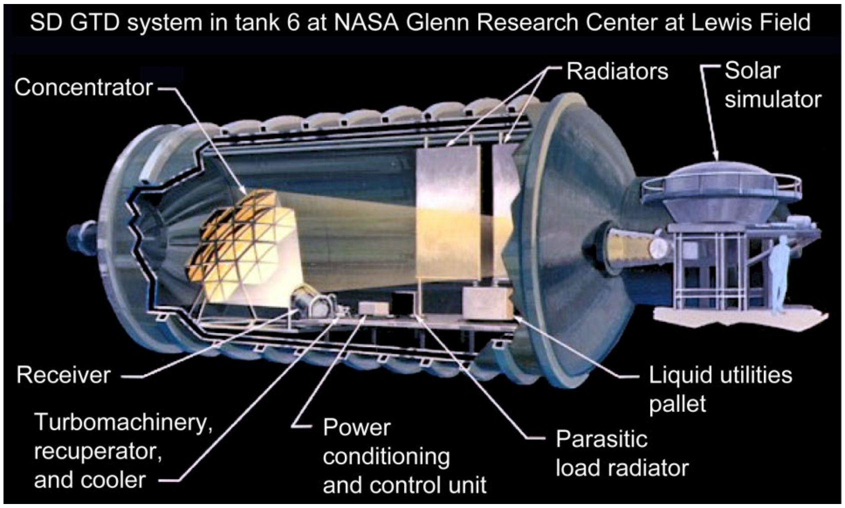


Figure 5.—Diagram of Ground Test Demonstrator at Glenn using an offset parabolic solar concentrator.

Parabolic mirrors, like Cassegrains, must track the Sun. Because the focus of off-set parabolas is in front and below the concentrator, there is no need for a secondary concentrator. Therefore light is only reflected once before it reaches its focus, thus decreasing reflectivity losses. The ability to design a concentrator with the focus on or near the surface provides a significant benefit in integrating this concentrator geometry into an oxygen reactor design. Because currently designed reactor models are immobile, solar flux can be easily pointed towards a window in the reactor, directly illuminating regolith. This configuration would work most effectively at the Moon's poles, such as the lunar South Pole, where the lunar surface is nearly in constant illumination by the Sun (Ref. 6). In fact, the spot could be focused in any direction perpendicular to the direction of incident sunlight, e.g., to the side or above the concentrator. This opens up the possibility for novel design opportunities for optical steering by secondary concentrators.

Another advantage to this geometry is that the parabolic mirror can be configured so its entire mirror surface is sunlit, unlike Cassegrains, where some of the sunlight is blocked by the mirror-support structure. Because the parabola is essentially a small section of a much larger paraboloid mirror, the ray lengths of the offset parabola will always be longer than those of a similarly sized Cassegrain mirror. Thus, offset parabolic mirrors will either always have lower *CR*s, or smaller captured solar flux, than Cassegrains. Because of its ability to direct the concentrated sunlight off of its central axis, the geometry of an offset parabola lends itself to a number of applications such as illuminating the surface to provide 'thermal wadis' to store thermal energy to protect rovers and other assets from harsh thermal cycling effects (Ref. 18).

Compound Parabolic Concentrators (CPCs)

Compound parabolic concentrators (CPCs) are designed to capture light at a much larger acceptance angle than other concentrators, reducing the need for highly accurate tracking. Spot-based CPCs have the cross section of two deep parabolas; the edge of one parabola is the focus of the other, and vice versa. The geometry is rotated about the axis of concentration; incoming light is internally reflected and eventually focused at a spot near the base. Tracking does not need to be as precise or accurate with these concentrators, because they can have a fairly large acceptance angle of up to 45°, depending upon the design (Ref. 19). Use of a CPC primary concentrator would require some degree of tracking to keep incoming solar radiation within the concentrator's acceptance angle.

CPCs are manufactured as both hollowed mirrors and dielectrics (lenses). Examples of each type are shown in Figure 6 and Figure 7 respectively. The largest theoretical *CR* of all CPC's, mirror-based or dielectric, is defined by Equation (5) (Ref. 19):

$$CR = \frac{n^2}{\sin^2(\theta_{\max})} \tag{5}$$

In a mirror-based CPC, the refractive index n is assumed to be one. As shown in Equation (5), the *CR* is inversely proportional to maximum acceptance angle; higher-concentration CPCs have a small outer diameter and a long length. Consider a CPC used as a primary concentrator; the diameter of the CPC would need to be a similar to the diameter of the solar flux. The length of the CPC would be considerably longer; both the volume and weight of such an instrument are not feasible for use as a primary concentrator.

Dielectric CPCs are also limited by another restriction; propagating light is assumed to be totally internally reflected by concentrator walls. The maximum concentration due to this restriction is shown by Equation (6) (Ref. 19):

$$CR_{\max,\mathrm{CPC}} = \frac{1}{\left(1 - \frac{2}{n^2}\right)^2} \tag{6}$$

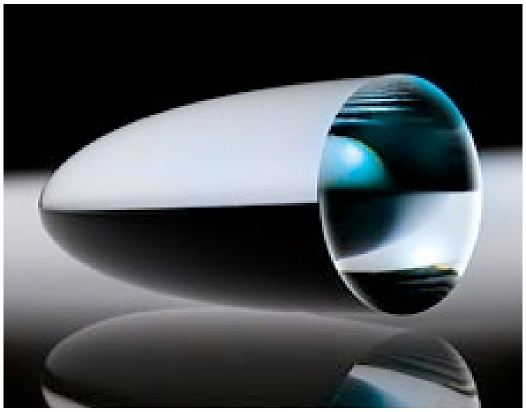


Figure 6.—Hollow-mirror CPC.

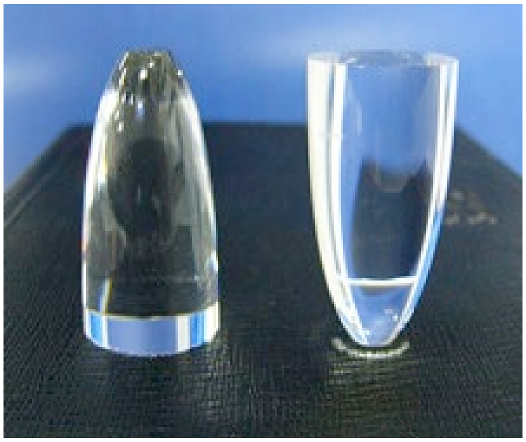


Figure 7.—Dielectric (lens) CPC.

This equates to a maximum concentration of $CR_{\max,\mathrm{CPC}}$ of 81 for an example refractive index of $n = 1.5$ for crown glass (Ref. 11). Such concentrations are too small for achieving temperatures necessary for melting lunar regolith by itself. However, there is still a possibility for CPCs to be used as secondary concentrators.

Trough (Line-Focus) Designs

As discussed previously, the most common concentrator shape is a parabolic dish, or cone in which incident light is directed towards a spot focus of a specified area. Another approach is to utilize a trough or cylindrical configuration, which sweeps out a parabola along a line perpendicular to its two-dimensional shape. Incident light will then focus onto a line. Two main types of line-focus concentrators have been developed; one, well known for its terrestrial applications, is a parabolic trough. This technology is used in large-scale solar plant designs (Ref. 20); it could also be adapted for use in water purification, for example. The SLA, another line-focus technology developed in recent years, uses arched Fresnel lens concentrators to direct light towards a desired focus as displayed in Figure 8 (Ref. 2). The SLA technology offers state-of-the-art space or surface operational performance in the following metrics: aerial power density (W/m^2), mass-specific power (W/kg), stowed power density (kW/m^3), operating voltage (V), and array power capacity (kW to multi-MW) (Ref. 2). Arrays can be manufactured using a roll-to-roll process, making it easy to rapidly mass-produce any desired quantity (Ref. 10).

However, in thermal applications where high temperatures are necessary for processes such as oxygen production, a line-focus design falls short. The maximum possible *CR* of a line concentrator, as bounded by thermodynamic limits for solar concentration (Ref. 1), is described by Equation (7):

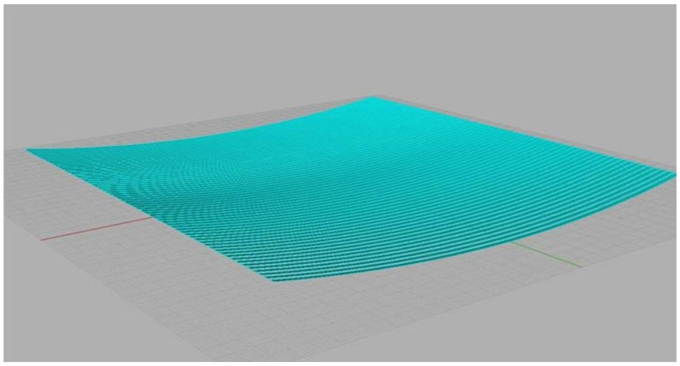
$$CR_{\mathrm{2D}\,\max,Th} = \frac{1}{\sin\theta_{\mathrm{Sun}}} \tag{7}$$

Because the half-angle of the Sun’s incident light (θ_{Sun}) is 0.275°; maximum concentration of a linear, or trough concentrator, as defined by its thermodynamic limit is approximately 208, and realistic linear concentrators aim for a maximum *CR* of about 30 (Refs. 1 and 13). From Figure 1 it is apparent that trough configurations do not have sufficient concentration ratios to achieve temperatures required to process lunar regolith for oxygen production or similar processes.

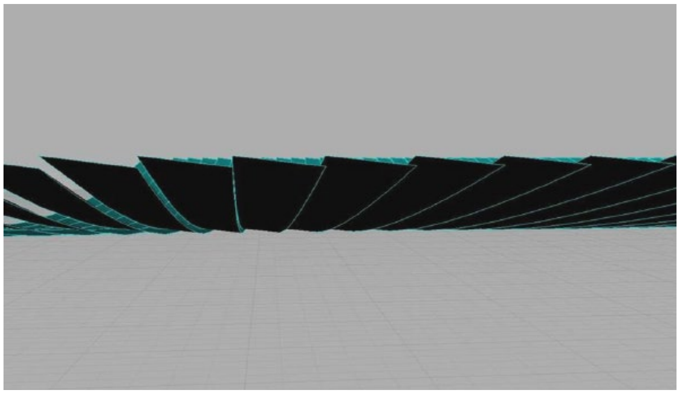
Fresnel Reflector

In order to achieve high temperatures for ISRU processing while minimizing re-radiative losses, high concentration ratio solar concentrators are needed. To achieve this reflector configuration in a composite without complex curvature surfaces, DR Technologies developed a point focus Fresnel reflector configuration under a small business innovative research (SBIR) program managed by Glenn. The reflector uses an array of simple curvature parabolic strips, each with a small line focus, and each oriented to overlay the line focus into a central focal area, thus simulating a point focus concentrator, as shown in Figure 9.

Figure 8.—The Stretched-Lens Array (SLA) focusing incident light onto PV collector.



(a)



(b)

Figure 9.—(a) Model 1.5 by 1.5 m Fresnel Reflector using 60 strips. (b) Edge view showing individual strips.

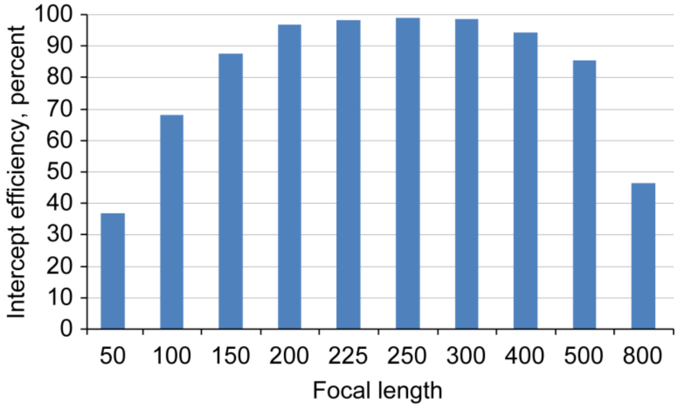


Figure 10.—Intercept efficiency as a function of focal length for a 150 cm aperture, leading to an F/d of 1.5, see Figure 11.

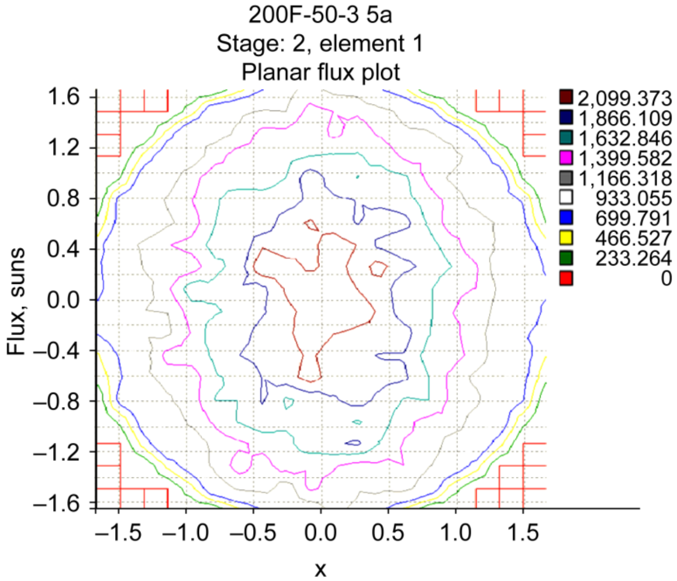


Figure 11.—Flux distribution predicted by SolTRACE for the optimized F/d of 1.5.

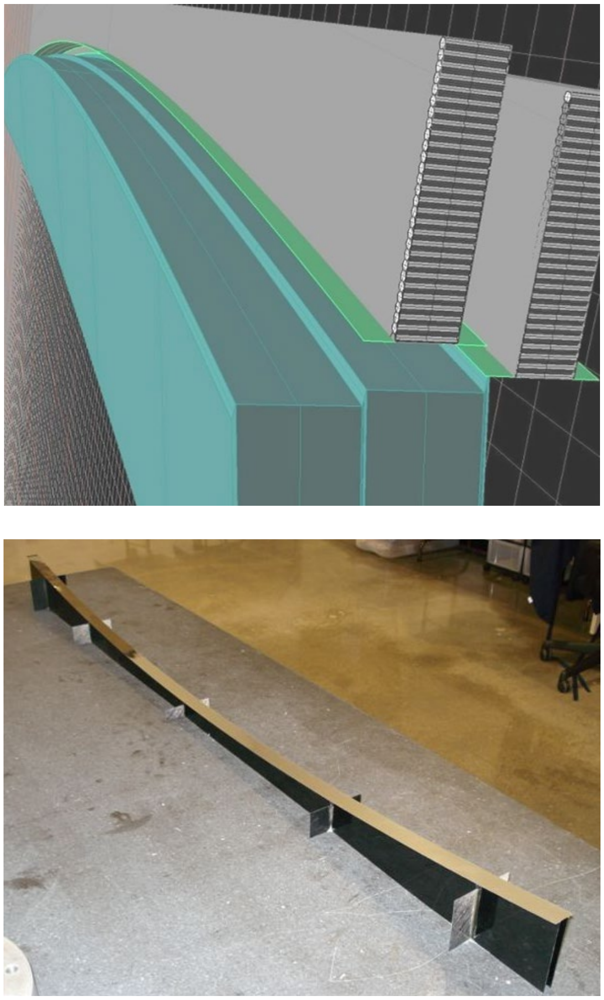


Figure 12.—Implementation of Fresnel mirror on composite rib, and assembled on a positioning tool using a frame that fixed the mirror strip position.

This design results in several significant advantages. An array of simple curvature strips can be fabricated without using an accurately machined mandrel as would be needed for a parabaloidal dish, with each strip cut from a replicated mirror flat and then mounted on an accurately machined structure. The Fresnel reflector has a low cross-section, which makes packaging for shipment and launch considerably more efficient; independently mounted strips are less likely to incur global thermal distortion errors.

Concentrator design synthesis used SolTRACE code provided by National Renewable Energy Laboratory. The model drove design trade-offs that varied width, length and number of Fresnel strips in the concentrator, focal length (Figure 10), overall aperture, and then determined the number and distribution of rays falling within a selected aperture size by ray tracing, while considering realistic mirror slope and specularity errors. These trade-offs drove design parameters to achieve high intercept efficiency with a maximum concentration ratio of 2100, as shown in Figure 11, showing flux distribution for an optimized Fresnel concentrator.

A Fresnel reflector model was developed using mirror strips of Graphite Fiber Reinforced Composite (GFRC) fabricated using a proprietary mirror replication process for high specularity. Each mirror strip was mounted on a composite rib structure, as shown in Figure 12 and Figure 13, and assembled into a frame using a placement tool. Illumination tests on the concentrator using a heliostat resulted in temperatures in excess of 1575 K. Higher temperatures should be achievable with an optimized absorber and secondary optic configuration.

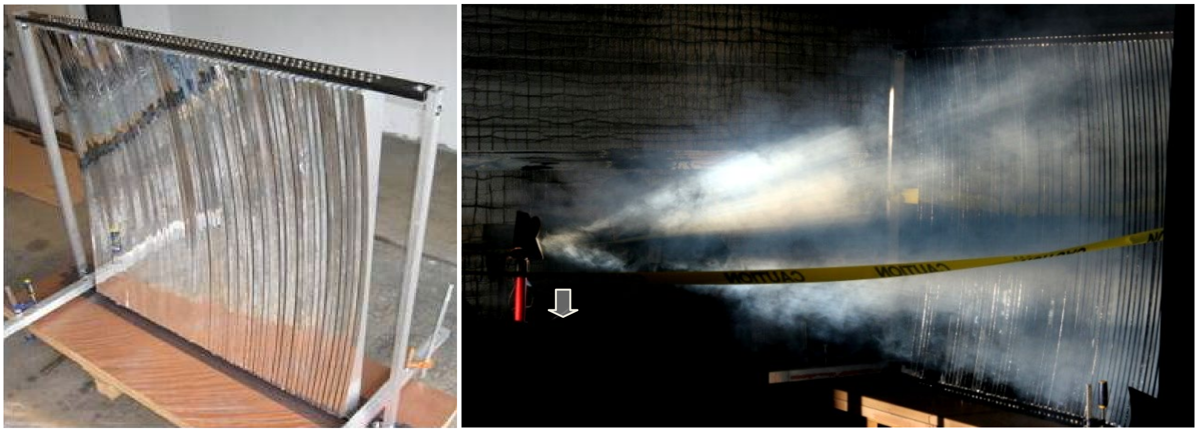


Figure 13.—Mirror test article and illumination testing using fog machine for visual feedback.

Secondary Concentrators

Secondary concentrators are optical devices used to further concentrate focused light after being directed by an initial concentrator, or to move focused light to a desired location. Such technology has been designed and tested for effectiveness; a sapphire refractive concentrator, see Figure 14, has demonstrated some potential promise (Ref. 21). Although most secondary concentrators developed are lenses, mirrors could also be used. Secondary concentrators could capture solar energy obtained from large flexible or inflatable concentrators, which typically have lower *CR*s due to inaccuracies in their shapes, projecting it into a smaller spot thereby enhancing their *CR*. As optical media affects light, there are inherent losses; the tested sapphire concentrator has a calculated transmission of 87 percent (Ref. 21). Losses could be minimized and *CR* increased, however, with effective design and testing. As discussed above, a CPC's most effective use could be as a secondary concentrator to a Cassegrain or offset parabola. Secondary concentrators could also be used to direct solar flux into a designated position for prolonged time periods; the primary concentrator's moving spot could be pointed towards a secondary concentrator, that points towards regolith or an energy transfer device. Such technology, however, would require complex control systems, and is likely to increase losses induced by Sun tracking and inhibits its ability to capture end angle light rays. An example of a secondary lens system for focusing and further concentrating sunlight is shown in Figure 15. This system utilizes a combination of lenses and mirrors to be able to concentrate and move the focus.

One significant issue with secondary concentrators, however, is likely to be material selection. Though sapphire was chosen for its ability to be used under extreme temperatures, a recent test at Glenn resulted in cracking and failure once a prototype reached 1550 K (Ref. 21). The primary concentrator chosen will focus (solar) light at least hundreds, preferably thousands, of times incident sunlight, and as such, the secondary concentrator must be much more resistant to EM radiation and intense heat for prolonged periods of time. Slight imperfections in secondary concentrators are likely to produce high operating temperatures due to high light flux from a primary concentrator. Therefore, secondary concentrators should not be considered an as afterthought, but as an integral component of the overall system for effective concentrator design.

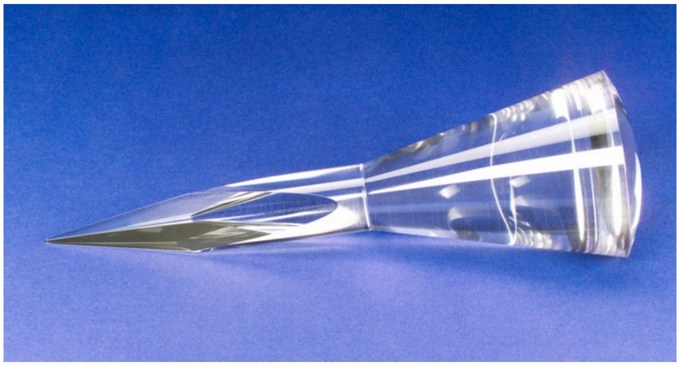


Figure 14.—Refractive Secondary Concentrator.

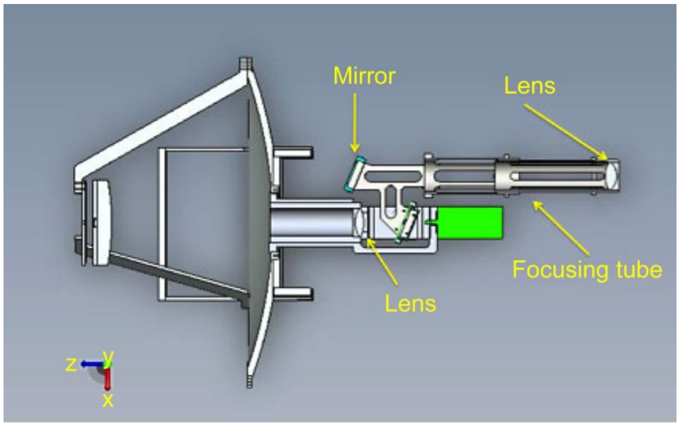


Figure 15.—Cassegrain Concentrator with Optical-Concentrating and Focusing System.

Reactor Designs

Producing oxygen in-situ on the Moon can provide significant benefits and overall cost savings to future missions. Earth has a relatively large gravity well with an escape velocity of 10.4 km/s (Ref. 7). This escape velocity requires tremendous resources to launch any significant object into orbit, and even more to bring along fuel necessary to maneuver, once in orbit. The Moon on the other hand has one-sixth gravity of Earth. A launch from the Moon to Earth orbit would require much less propellant than launching a similar vehicle from Earth. The ability to effectively and efficiently produce oxygen from lunar surface materials must be realized to effectively harness these benefits. Both carbothermal and hydrogen reduction processes have shown potential for producing oxygen from lunar regolith and therefore can achieve that mission-enabling goal.

Hydrogen Reduction

Hydrogen reduction makes use of ilmenite ($FeTiO_3$) in lunar regolith as well as H_2 gas (likely from water splitting) to produce pure iron (Fe), TiO_2 and H_2O. The temperature required to carry out this reaction is approximately 1300 K. A simplified design, shown in Figure 16, of a hydrogen reduction reactor utilizes an auger to move regolith through the reactor as well as heating regolith with the blades (Refs. 22 and 23). A heat pipe would be used to evenly heat the auger by distributing the energy from the solar concentrator, focusing light onto the heat pipe. The auger blades could also be used to introduce hydrogen by providing a fluidized bed of regolith. There is great potential for this process, but there still remain a number of challenges in reactor design and operation. For example, hydrogen embrittlement caused by hydrogen gas permeating a metal structure can cause certain metals to crack, promoting premature failure; some metals and alloys are more susceptible to hydrogen embrittlement.

Carbothermal Reduction

Carbothermal reduction relies on temperatures of at least 1800 K to extract oxygen from all of the major composite constituents of lunar regolith as shown in Table 1. A system being tested by Orbital Technologies Corporation (ORBITEC) is detailed in Figure 17 (Ref. 24). A carbothermal reactor must melt regolith to initiate the reaction; this melt is achieved by concentrated solar energy heating a small amount of regolith and using the surrounding regolith as thermal insulation. Excess space above the regolith is used to flow methane. Methane reacts with molten regolith to eventually produce water, which is then split (electrolyzed) to produce oxygen and hydrogen. Hydrogen gas is reused in the process, generating methane from carbon monoxide, the product of methane reduction of metal oxide(s) (Ref. 24).

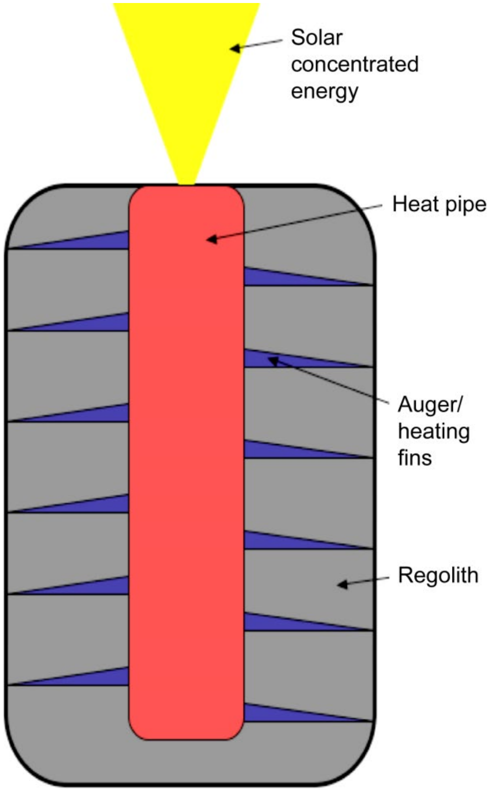


Figure 16.—Simplified diagram of Current Hydrogen Reduction Reactor Design.

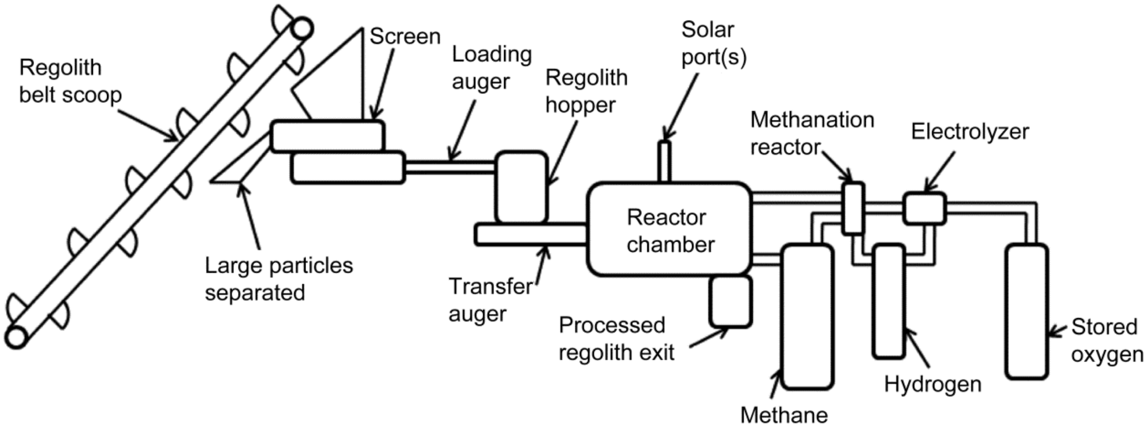


Figure 17.—Diagram of current ORBITEC carbothermal reduction reactor with features identified.

Solar energy is focused through a window into the reactor chamber. There are other methods that could be implemented to concentrate solar energy onto regolith, including heat pipes or fiber optic lines. There are design concerns for each of these approaches. For example, using a window to concentrate sunlight in the chamber could result in that window being obscured by clinging of regolith particles in the reactor. Also, the chamber has free flowing gas, which could pick up dust and interfere with focusing of light. It should be noted that a sufficient gap is required between the regolith and window, otherwise, a temperature gradient across the window can cause excessive thermal stresses potentially causing failure.

The ORBITEC carbothermal regolith reduction module (CRRM) was initially tested with a CO_2 laser to simulate concentrated solar energy. The CO_2 laser energy passed through a zinc selenide window and illuminated a bed of lunar regolith simulant located at the bottom of the sealed processing chamber within the CRRM. Laser energy absorbed by regolith simulant caused rapid, localized heating. Given a sufficient laser energy flux, a pool of molten simulant would form surrounded by unmelted simulant due to low thermal conductivity of regolith simulant. Surface temperature of molten simulant was determined by the laser energy flux; this heating approach worked well as long as the zinc selenide laser window remained completely clean during operation. Surface temperatures of molten regolith simulant in excess of 2075 K were achieved and maintained.

If any deposits or particulates accumulated on windows, some laser energy would be absorbed causing window heating and eventual failure. A solar concentrator system was recently developed by PSI and integrated with ORBIRTEC's CRRM. The integrated system was successfully operated for nearly two weeks during the 2010 International Lunar Surface Operations and ISRU Analog Test on Mauna Kea in Hawaii shown in Figure 18. Concentrated solar energy was delivered into the processing chamber through a quartz rod, as shown in Figure 19. Since regolith surface temperature was determined by solar energy flux, varying the distance of the quartz rod above the surface controlled regolith temperature.

As with the zinc selenide laser window, the quartz rod efficiently transmitted concentrated solar energy into the processing chamber when it was clean. However, transmission performance of the quartz rod degrades rapidly if any deposits or particulates accumulate on its surface. Deposits on the end of the quartz rod will absorb concentrated solar energy, both attenuating the solar energy delivered to the regolith and quickly heating the quartz rod until failure. Unfortunately, keeping the quartz rod clean within the processing chamber proved to be more difficult than expected.

The end of the quartz rod needed to be located 2.5 to 4 cm above the surface of the regolith simulant to maintain the temperature of the molten regolith at 1975 to 2075 K. The carbothermal reduction of regolith produces silica vapor that will coat interior surfaces of the processing chamber. In addition, rapid production of carbon monoxide in molten regolith causes molten regolith to splatter on nearby surfaces as CO gas bubbles break. To prevent potential silica vapor deposits or molten simulant splatter from accumulating on the end of the quartz rod, ORBITEC enclosed the end inside a clear quartz window. A thin layer of gas blowing across the bottom of the quartz window was used to keep the quartz window clean during processing.

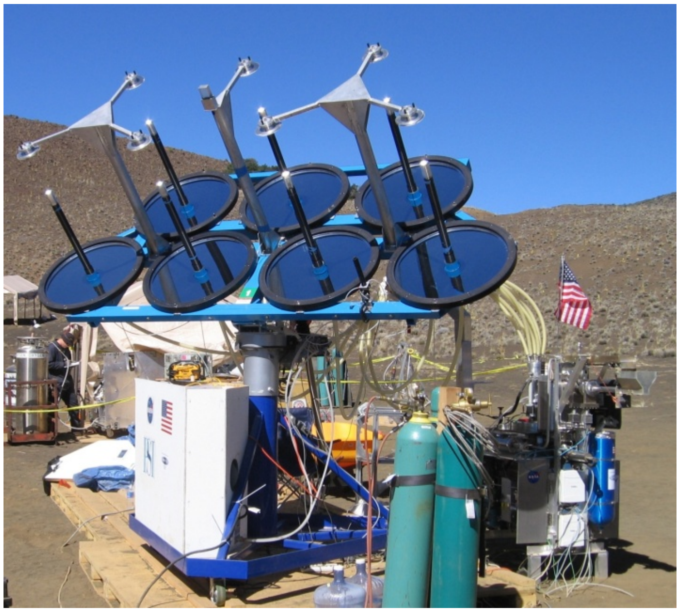


Figure 18.—Photograph of the Solar Concentrator Array (left) with the Carbothermal Regolith Reduction Module hardware (right).

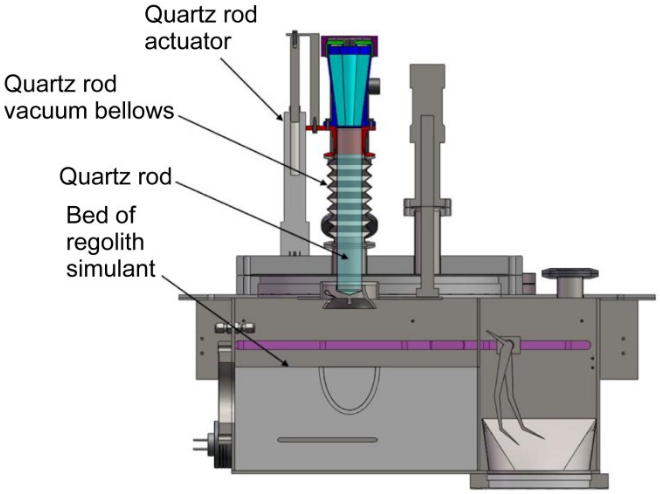


Figure 19.—Cross-section view of the processing chamber within the Carbothermal Regolith Reduction Module (CRRM).

Figure 20 shows the interior of the processing chamber after a carbothermal reduction-processing batch. Note the layer of silica vapor that extends from processed regolith simulant. When a sufficient gas flow rate was used, silica vapor was blown away from processed regolith by gas flow across the bottom of the quartz window. If the gas flow is not optimized, silica vapor accumulates on the quartz window and damages it as seen in Figure 21. Although the layer of gas blowing across the quartz window was very effective at preventing any silica vapor from accumulating on the window, glass splatter from molten regolith remained a problem if the bottom of the quartz rod was moved less than 3 cm above the regolith surface during processing. Figure 22 shows a photograph of the quartz window after a carbothermal reduction-processing batch where the end of quartz rod was located 2.5 cm above the regolith surface; note numerous glass beads on the quartz window surface.

ORBITEC measured improvement in delivered solar energy due to the presence of a protective quartz window. Quartz windows with and without anti-reflection coatings were tested. The energy loss with an uncoated quartz window was ~7.5 percent due to Fresnel reflection loss. When a quartz window with a VIS-IR anti-reflection coating was used, the energy loss was reduced to less than 1 percent. However, when a coated quartz window was used for a carbothermal reduction test, the anti-reflection coating was damaged and began to flake off. It appears that the window became too hot and the anti-reflection coating failed. An uncoated quartz window was used in subsequent tests of the CRRM.

There are several important lessons learned from this project. First, a quartz rod is an effective and efficient method to deliver highly concentrated solar energy into a carbothermal reduction-processing chamber. Using this delivery approach,

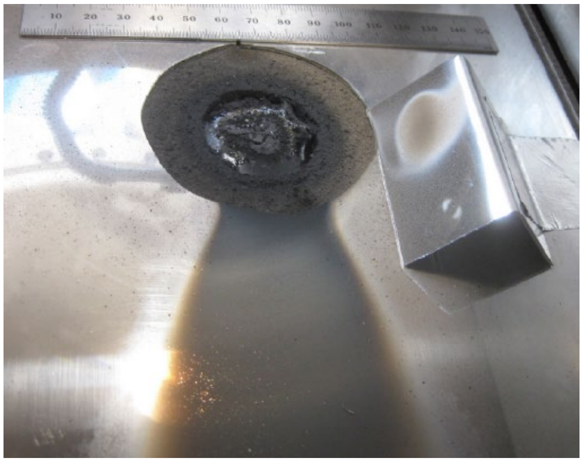


Figure 20.—Example of silica vapor produced during carbothermal reduction processing of JSC-1A lunar regolith simulant with solar energy.

Figure 21.—Damage to a protective quartz window due to accumulated silica vapor.

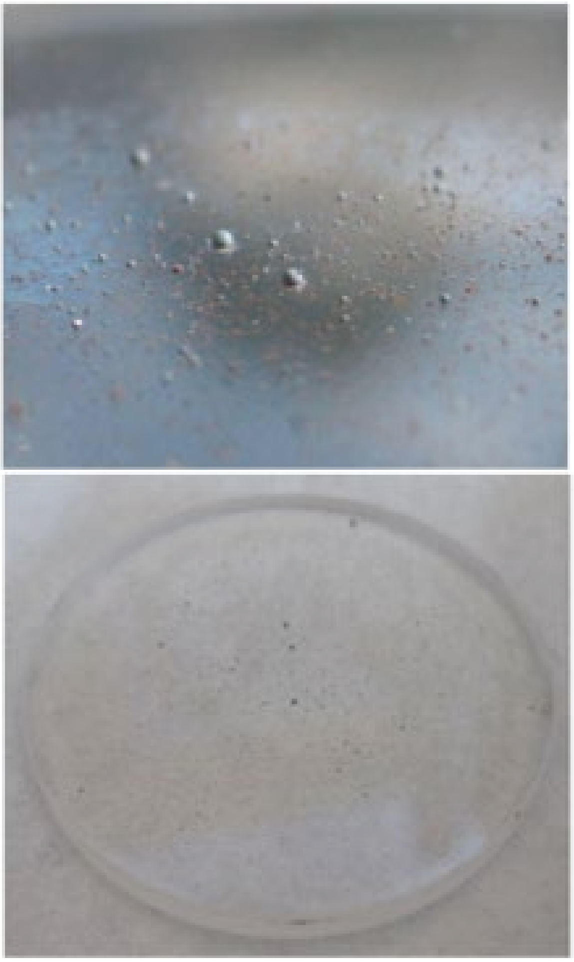


Figure 22.—Magnified view (top) of small glass beads accumulated on bottom of protective quartz window, normal view on the bottom.

molten regolith surface temperatures in excess of 2075 K were easily achieved. Second, varying the distance between the end of a quartz rod and regolith surface will impact the temperature of the molten regolith. Third, special precautions must be taken to protect any optical surfaces within a carbothermal reduction-processing chamber, such as the end of the quartz rod. Any deposits or accumulation of particulates will lead to rapid heat and degradation of optical surfaces. Finally, anti-reflection coatings can be very effective at reducing Fresnel reflection losses. However, care must be taken to ensure that coating can survive thermal stresses.

Design Implementation

Consideration of a complete system for material processing on the lunar surface requires that numerous other design issues be addressed in addition to the concentrator geometry. In order to operate on the lunar surface, a concentrator must survive launch and be resistant to lunar environmental challenges. The presence of a hard vacuum, solar wind, micrometeorites, EM radiation, and constant thermal cycling of the range of ~300 K are primary issues to consider. Available technology options, such as lenses vs. mirror concentrators, and rigid vs. flexible concentrators, must be compared and contrasted to determine the suitability of each technology. Solar thermal component options available to harness and transfer concentrator energy to heat regolith must be addressed as well. What follows is not an exhaustive list of every necessary design consideration, but provides an overview of design issues that must be considered when developing effective lunar-based solar concentrators.

Mirror Versus Lens Concentrators

Typically, mirror-based concentrators are developed for thermal applications and lens-based concentrators have been associated with PV applications. These specific applications seem to be based largely on history and tradition (Ref. 1). The environment, design, manufacture, and operation of these systems for lunar processing are inherently challenging and complex. Design heritage, cost, launch vehicle capabilities, packaging, mass environmental compatibility and operational lifetime factor into optimizing and matching specific concentrator technology application(s). In addition, because mirror concentrator designs for thermal applications have a legacy of research, testing, and development, mirror concentrators are likely to continue to be developed and studied for these applications. The same logic applies to lens concentrators for PV applications.

From a theoretical perspective, lenses are actually a much better choice for concentrators. The maximum *CR* of a solar image on the absorber of a three-dimensional mirror concentrator, bounded by thermodynamic limits for solar concentration, is described by Equation (4) and is roughly equal to 46,000 (Ref. 1). Theoretical optical constraints dictate that a solar concentrator made from a refractive material can reach higher concentrations than reflective concentrators, as defined by Equation (8) (Ref. 1).

$$CR_{3\mathrm{D}\,\max,Th} = \left(\frac{n}{n_{surr}\sin(\theta_s)}\right)^2 \approx 97{,}700 \qquad (8)$$

The index of refraction n_{surr} in air equals 1 and n for crown glass equals 1.5 (Ref. 1). However, lens effects such as spectral shifting and groove darkening reduce the actual light concentrating capability of a lens. Because of intrinsic physical deficiencies of lenses, during actual usage, mirror reflectors usually have a higher effective *CR* than most lens concentrators. However, lenses do have several advantages over mirrors: angle incidence errors caused by errors in Sun tracking or concentrator shape distortions are drastically less with lenses than with mirrors. Fresnel lenses with the unique arch shape of the SLA actually provide more than two orders of magnitude better shape error tolerance than reflective concentrators, or than conventional flat Fresnel lens concentrators; when SLA materials are damaged, these devices continue concentrating light effectively (Ref. 2). In fact, for mirror-based thermal concentrators, accuracy of tracking mechanisms need to be approximately one hundred times better than for lens-based concentrators (Ref. 1).

Consideration of manufacturing techniques and possible materials for lunar surface operation are significant concerns for utilizing lenses. Lens materials usually come in either glass, or transparent plastics. When glass lenses are used as primary lens material, concentrators become very heavy. Previous ISRU oxygen production studies estimate the concentrator or concentrator assembly area needs to be at least 14.38 m^2 to capture sufficient solar flux; leading to use of large, heavy lenses as primary concentrators (Ref. 3). Furthermore, glass is a brittle material that has potential to crack or shatter due to intense stresses experienced by launch. Plastics, such as space-qualified silicone DC 93-500 used for a SLA, must be held in place by an external skeletal structure (Ref. 2). Plastics can also be degraded by space environment effects such as atomic oxygen, UV, micrometeoroids, and must be protected by oxide films. Metals and composites used in mirror materials are much less likely to be affected by environmental effects. Scaling of technologies is also a factor; it is traditionally easier and lower cost to make larger mirrors with high *CR*s than larger lens concentrators with similar *CR*s.

Because tradition has linked mirror concentrators and thermal applications, and lens concentrators and PV applications, companies specializing in manufacture of such technologies have been formed which reinforce such traditional links. However, concentrator options are widely available for multiple functions by different companies: Optiforms, Optical Mechanics, and Hardric Laboratories specialize in manufacturing mirrors meant for a spot focus. Minnesota Mining and Manufacturing (3M) produces sheets of space-rated silicone for line-focus concentrators of any size; there are few if any companies who specialize in the production of commercial point-focus Fresnel lens concentrators (Ref. 2).

Rigid Versus Inflatable/Flexible Concentrators

Rigid concentrators are self-supporting; they have enough structural rigidity to maintain their shape without external structural support. Flexible concentrators (Figure 23), however, forego structural rigidity for very low weight and small storage volume (Ref. 12); they must, however, be maintained in a semi-permanent shape by some external structure during operation or rigidized after deployment. One approach is that of an inflatable concentrator kept rigid by trapped gas inside. Such technology has a much higher specific power rating, or power per unit mass, than rigid concentrators (Ref. 22). This means inflatable concentrators can be made much larger than rigid concentrators of the same mass and capture much more solar flux.

Inflatable solar concentrators have been produced that capture an effective solar flux diameter of over 4 m (Ref. 22). Flexibles and inflatables, however, usually maintain their shape by a combination of some supporting back structure along with the inflating gas. Such technologies however, have a much higher shape error than a polished rigid mirror concentrator or a finely milled Fresnel lens concentrator. Thus, the spot size of inflatable concentrators is much larger than similarly sized fixed concentrators. Low-weight rigid concentrator assemblies are possible, like the rigid concentrator hexagonal assembly made for the James Webb Space Telescope (Ref. 15). Employment of such designs, however, is likely to drastically increase manufacturing costs.

Figure 23.—Flexible 4 m by 6 m offset parabolic concentrator.

Although inflatable concentrators have advantages of lower mass and stowage volume over rigid concentrators, there are other issues that limit their applicability. The inflated area that actually focuses light has to be inflated from both sides; therefore, for mirror concentrators, the initial material that incident light travels through must be transparent. Most materials that are not gas permeable and can take extended operation in a vacuum are not completely transparent; potential losses over the usable EM spectrum increase. Another important issue with flexible concentrators is the effective life of such technology in the hazardous space environment; most usable plastics are less resistant to space and lunar environmental effects than metals and glass. Micrometeoroid puncture analyses have been performed for flexible structures in low-Earth orbit, but lunar projectile fluxes have yet to be studied in detail. Atomic oxygen causes a chemical reaction with space inflatables that can erode or build up a growth on the polymer surface, causing material degradation. Ultraviolet radiation and solar wind serve to break chemical bonds and thereby decrease strength in exposed materials. Silicones are some of the most resistant materials to harmful radiation, and silicon oxides (SiO_x) and related glasses are particularly resistant to atomic oxygen effects (Ref. 25). UV darkening is known to occur for many plastics; UV-resistant coatings to protect space-rated silicones are being developed with promising results, but such technologies must undergo sufficient testing (Ref. 2). Transparency of specific materials with coatings and their wear over prolonged periods of time must be further studied.

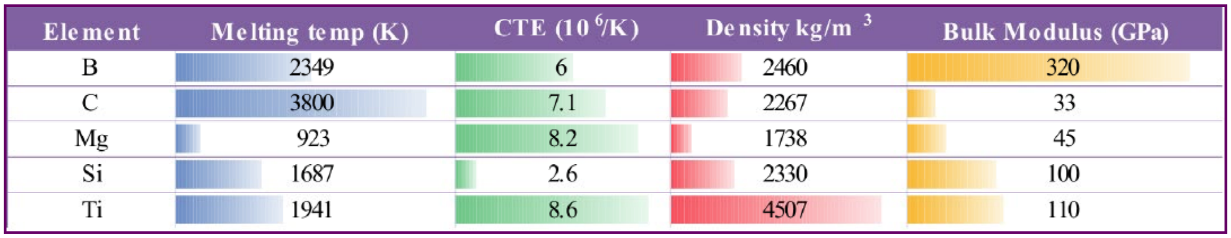
Rigid Mirror Concentrator Material Overview

Material requirements for a rigid mirror concentrator technology are as follows:

- High Reflectivity
- Low Coefficient of Thermal Expansion (CTE)
- Strong (High Tensile Stress or Modulus of Elasticity)
- Light (Low Density)
- Inexpensive, if possible
- Reliability over prolonged periods of operation during harsh lunar exposure

Many of the material requirements are straightforwardly related to effective lunar surface operations. For example, a high ultimate strength and modulus of elasticity means the material is strong and resistant to deformation. Low-density materials mean lighter weight structures and lower cost to launch. Reliability means the material will not break, creep, falter, or wear in any of a number of ways in which material breakdown occurs. A low CTE means that during large temperature swings on the Moon, materials are resistant to effects of thermal stresses and deformation.

Most materials considered for mirrors do not have all of these qualities; copper, silver, gold, platinum, and rhodium, which have the highest reflectivity, have high CTE's, are



Element	Melting temp (K)	CTE (10^{6}/K)	Density kg/m^{3}	Bulk Modulus (GPa)
B	2349	6	2460	320
C	3800	7.1	2267	33
Mg	923	8.2	1738	45
Si	1687	2.6	2330	100
Ti	1941	8.6	4507	110

Figure 24.—Graphical comparison of candidate elemental substrate materials chosen for optimal values of melting temperature, coefficient of thermal expansion (CTE), density, and bulk modulus of elasticity.

heavy (dense), and the final three are quite costly (Refs. 26 and 27). Aluminum, which can produce a mirror finish with a reflectivity of 91 percent, is light and strong, but has a high CTE (Ref. 16 and 28). Composite mirror technologies are being developed where a light and strong substrate is used for the structure and a reflective material is deposited on its smooth surface. Atomic layer deposition (ALD) processes are being considered for mirror film application; the deposited film is thin enough that there are minimal thermal stresses between substrate and mirror coating. Mirror deposition for optical thin films has been shown to be effective for deposited layers on the sub-micrometer level. More research must be conducted on substrate-mirror composites for lunar-surface solar concentrator operating simulations to demonstrate that they can be made with sufficient surface quality and that high-performance reflective coatings can be deposited (Ref. 29).

A preliminary consideration of potential elemental materials that could be used as simple mirror substrates is summarized in Figure 24; five candidate elements are considered, and four physical properties, that will impact their effectiveness are compared: CTE, density, melting temperature, and module of elasticity. Silicon, boron, carbon, magnesium, and titanium are all potential substrate candidates due to their high strength, relatively low density and low CTE. Silicon has the lowest CTE; titanium, known for its aerospace applications, has the highest. A detailed study of advanced materials such as metallic alloys, ceramics, or composites as mirror substrates should also be considered (Refs. 26, 27, and 30 to 33). The unique properties of these engineered materials would need to be evaluated to access their applicability to lunar and/or space environments.

More advanced technologies and concepts include use of electro-active functional materials, such as ionic polymer metal composites (IPMC's) as mirror substrates. Originally conceived as an alternative for prosthetic muscle material, the mirror surface itself could deform to adjust to different conditions and a means of actively focusing the mirror. The polymer accomplishes this by deforming when exposed to an electric field. This technology holds significant promise in providing the ability to fine tune mirror focus during operation as well as redirecting the focus and potentially aiding in tracking.

Lunar Environment

The lunar environment provides several design challenges as well as potential opportunities. The Moon has a gravitational attraction of 1/6 Earth. Reduced gravity can make it awkward for humans to walk. However for structures and some processes, the lower gravity could be advantageous. Solar concentrators on Earth require bulky and heavy support structures to keep mirrors from distorting due to gravity and wind. The majority of deflections in parabolic systems on Earth are due to forces exerted by wind especially during a storm. On the Moon, with a hard vacuum of ~10^{-12} torr (Ref. 34), except for solar wind, there are no forces to cause any additional deflections. Another potential advantage from vacuum is heat transfer; there are no convection or conduction processes, save conduction through the lunar surface. This leaves radiation as the only appreciable heat exchange mechanism. This is advantageous for heating and processing of lunar materials since heat losses are minimized. A significant negative, however, is that reactions must take place in a pressure vessel to maintain internal gas pressure and provide a means of capturing reactants for processing. With radiation as the only means of heat transfer; temperature gradients across devices and components can become extreme because there is no atmosphere to help even out heat transfer and reduce these gradients.

A quite significant environmental challenge on the Moon is lunar regolith or dust. Average particle size of constituents of lunar regolith is about 70 μm, with 20 percent by weight of regolith being less than 20 μm (Ref. 35). Because of the small size and shape of regolith, there are three primary challenges to solar concentrator and oxygen production systems: dust clinging, abrasiveness, and clogging (Refs. 34 to 36).

i. ***Dust Clinging***.—The main concern with dust clinging is adhesion to optical surfaces. Dust becomes electrically charged allowing it to stick to a variety of surfaces (Ref. 35). A mirror lens, or window will transfer less light while coated in dust, which will greatly diminish system efficiency. Some technique must be devised to either keep dust off of concentrators and other optical components or be able to clear away dust that will inevitably coat optical surfaces during operation.

ii. ***Abrasiveness***.—The abrasiveness of dust can obscure and damage optical surfaces. During Apollo 17, scratching on Harrison Schmitt's Sun-shade prevented him from seeing in some directions (Ref. 34). Extensive scratching of solar concentrator mirrors would cause light to scatter due to small changes in the surface, which would once again negatively affect system efficiency.

iii. ***Clogging***.—Dust clinging can clog pressure vessels. This can affect seals as well as inlets and outlets, gears and motors. This issue will be very difficult for oxygen reactors. Both carbothermal and hydrogen reduction methods use gases for their reactions, which will create a pressure inside reactors. With a hard vacuum outside the reactor, some pressure seals will need to be in place. However, dust cannot be avoided because it is to be used as a reactant. Care will need to be taken for any moving part or opening, to avoid dust clogging.

A final environmental issue to be discussed is vacuum welding of moving parts. When two parts move relative to each other, there is friction and the surfaces of the two parts abrade each other. Earth's atmosphere has significant partial pressure of oxygen (21 percent), which reacts with exposed materials to create chemically inert coatings. In a vacuum, since there are no oxidation reactions that occur, parts of the moving system may bond to each other, potentially seizing up mechanisms. It will be a challenge to ensure that the tracking system on a lunar solar tracker or the moving parts in the reactor do not vacuum weld together.

Geographical Location

Selection of a specific concentrator technology will also be greatly influenced by lunar location. On the lunar surface there are two main types of regolith: older, brighter soils at high topographies, termed highlands, and darker basaltic lava flows of mare located at lower topographies (Ref. 3). A display of lunar topography is shown in Figure 25 (Ref. 37). The regolith of highlands and mare contain different minerals with varying elemental compositions; therefore different oxygen production processes are applicable in each of these areas. The hydrogen reduction process for producing oxygen can yield 1 to 5 percent of oxygen per unit mass of ilmenite (Ref. 38).

For comparison, the carbothermal oxygen production process requires higher temperatures to melt the regolith (~1900 K), but can be used with most of the minerals and other materials found in the regolith. The oxygen yield by weight, of the process, is approximately 15 percent (Ref. 3). For locations within mare regions, either hydrogen reduction or carbothermal reduction can be used as an oxygen production process. Since ilmenite is not found in usable amounts in highland regions (Ref. 39), carbothermal processing would need to be utilized. Higher temperatures and more precise concentrator optics would be required.

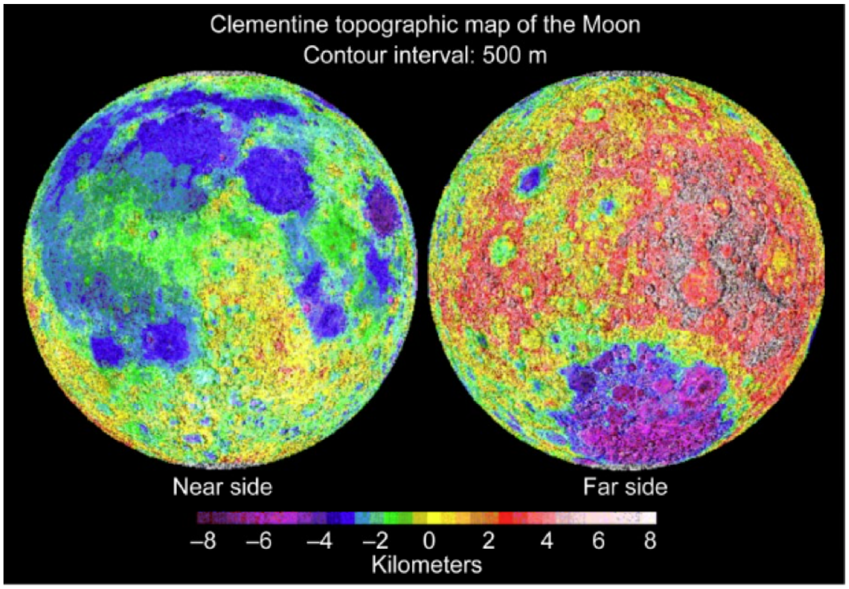


Figure 25.—Topographic map of the Moon determined by the Clementine mission of 1999.

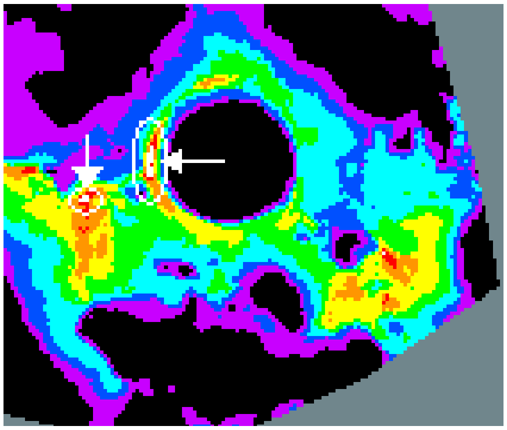


Figure 26.—Percentage of time with solar illumination during lunar winter. The arrows are pointing at the two regions that are illuminated >70 percent of the time during lunar winter; near the Shackleton Rim.

Though the mare and highlands have different regolith compositions, they both share one significant issue; for approximately 14 Earth days, almost the entire lunar surface is enshrouded in darkness (Ref. 40). Because the Moon's axis is tilted 1.5° from the ecliptic, the South Pole is almost constantly bathed in sunlight; during lunar summer, the entire South Pole is illuminated, and during lunar winter, the Shackleton crater and other small southern regions are illuminated by the Sun for more than 70 percent of the time (Ref. 40). Figure 26 shows percentage of time areas near the South Pole are illuminated during lunar winter. These locales would be ideal for a constantly operating solar concentrator that could generate approximately twice the amount of oxygen than an ISRU reactor anywhere else on the Moon. However, there are minimal deposits of iron and titanium located at the poles (Ref. 39). Less than 1 percent of ilmenite is present, hydrogen reduction would not be the preferred oxygen production method; carbothermal reduction or other non-mineral-specific processes must be utilized.

Additionally, long lunar days and nights in a hard vacuum result in significant thermal cycling; as discussed previously, this can cause thermal stresses to build up in materials. The average temperature range on the lunar surface is approximately 100 K during the night and 400 K during the day. The equation for simple linear thermal expansion is:

$$\Delta L = \alpha L_o \Delta T \tag{9}$$

Change in length is ΔL; thermal expansion coefficient of a material is α; L_o is starting length; and ΔT is change in temperature. For a 1 m-long aluminum strip, length would increase 6.9 mm during the transition from night to day. Consideration must be made during design to ensure that different parts of operating systems do not expand differing amounts, causing stresses, breakages, or unwanted gaps.

Energy Transfer Options

Most concentrators are required to Sun-track to be effective, and as the Sun "moves," so does a concentrated spot of solar energy needed to heat regolith. Models of regolith heating cycles require that regolith be illuminated and heated by stationary spots for 2.5 hr before it can be effectively processed (Ref. 41). Reactor assemblies being used for research and production are too large to move with a progressing solar spot, so in most cases, energy needs to be transferred to the stationary reactor. There are currently multiple concepts for thermal energy transport.

Direct illumination of regolith within a reactor is one option that can be utilized under certain operational conditions. In such a configuration, the focused concentrator solar spot would strike the regolith directly. For example, the South Pole offset parabola configuration would track the Sun's movement by rotating and would ideally have a stationary spot, making direct illumination possible for hours at a time (Ref. 9). Direct illumination would have minimal energy losses due to inefficiencies as additional optical components used to direct and channel concentrated sunlight would not be needed. Other than the efficiency of the concentrator mirror itself, the only other source of loss would be the window in which the concentrated sunlight would pass to enter the reactor chamber. For operating locations other than the North and South poles, concentrator configurations with additional optical components would be required to keep the spot in one place for extended periods of time. A secondary concentrator possibly made from a CPC or a refractive concentrator lens is a plausible alternative (Ref. 21).

Because of its low thermal conductivity, direct heating of the surface does not provide a good means of uniformly heating a batch of regolith. Only the top several microns would be effectively heated by direct illumination. For certain reactor designs this may be acceptable. For example, in a carbothermal reactor, reaction takes place at the regolith surface; regolith below the surface is used to insulate the chamber from the intense process heat. In other designs such as those for hydrogen reduction, uniform heating is more desirable and surface heating would not be an optimal approach.

Another form of energy transfer to be considered is the optical cable, as outlined above for a solar concentrator system for CRRM/oxygen production assembled by PSI (Ref. 16). A secondary concentrator located at the primary concentrator's focus would guide concentrated sunlight to a fiber optic cable bundle; this in turn would transfer and focus sunlight onto a stationary position within the reactor. The flexibility of fibers makes it possible for a concentrator to be tracking while illuminating a fixed spot within the reactor. Great strides towards effective optical cable technology have been realized through PSI's efforts, an assembly is shown in Figure 27. There are inherent losses in this type of light transfer system due to inefficiencies of optical cables. The complete concentrator configuration assembled by PSI had an efficiency of 37 percent, though use of higher quality components would increase system efficiency (Ref. 16).

Figure 27.—Optical cable assembly designed and utilized by Physical Sciences Inc. (PSI).

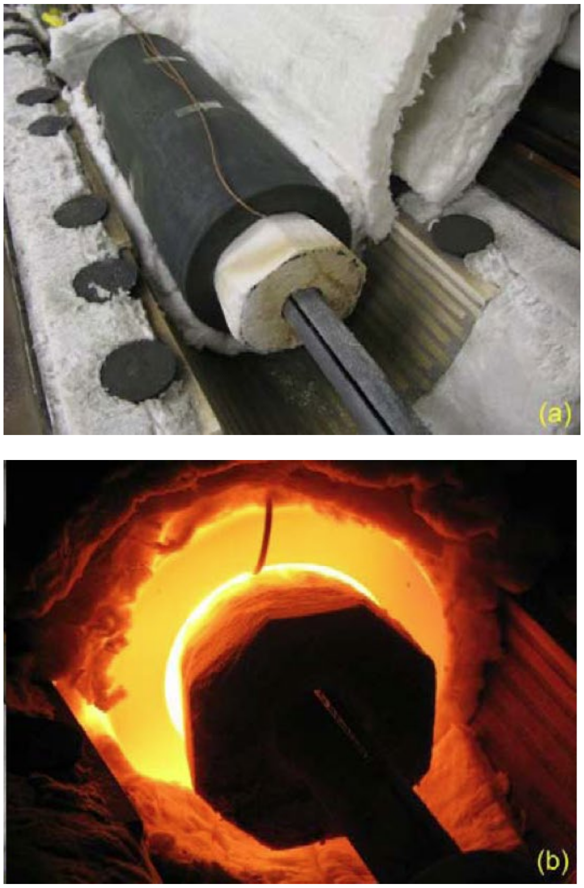


Figure 28.—(a) Demonstration heat pipe-test set up and (b) heat pipe demonstration operating at 1325 K using a Kanthal Heating Element.

Heat pipes are also being considered as an alternative technology for heat transfer; see Figure 28 (Ref. 41). Incident solar radiation is focused onto a heat pipe, using solar energy to evaporate the working fluid, the heat pipe would transfer heat to the regolith as the fluid condenses. Heat pipes provide isothermal heat transfer into the reactor, which increases lunar regolith processing efficiency (Ref. 41). Heat pipes also make it possible to transfer heat throughout the reactor thereby providing more uniform heating than that achieved by direct surface illumination (see Figure 16). Unlike an optical component, solar energy can be incident upon a heat pipe at very large acceptance angles, up to 90°. Fiber optic cables require solar energy to be incident at an angle less than 20°. This enables heat pipes to accept incoming sunlight from a concentrator over a range of angles, simplifying tracking and transmission of solar energy from the concentrator.

There are issues with use of heat pipes at high temperatures, for example, with the carbothermal process. For the heat pipe to effectively transfer heat to regolith it must be in direct contact. In the carbothermal process, high reaction temperatures and molten regolith provide a harsh and corrosive environment for heat pipes. Material buildup on the heat pipe is a significant concern as well as corrosion and/or oxidization of the surface. This would lower the thermal conductivity of the heat pipe, and thus the effectiveness as well as potentially lead to its failure. Heat pipes are better suited for processes that remain below the melting temperature of regolith, such as hydrogen reduction.

Heat pipes are rigid; designs include heat pipes attached to a tracking concentrator or heat pipes inside the reactor as a heat collection cavity. Many issues with keeping the spot stationary that apply to direct illumination also apply to heat pipe technology. Mobile or flexible heat pipes might be an option for such a technology, however, and should be further studied. More research needs to be conducted on materials that enable effective operation of heat pipes at temperatures in excess of 1900 K, needed for carbothermal reduction (Ref. 24).

Conclusions

Solar concentrator technology for ISRU-based oxygen production requires high temperatures for regolith processing. Several different designs, materials, and energy transfer options have been surveyed, each has inherent advantages and disadvantages. Some technologies are adaptable for multiple oxygen reduction sites (lunar poles or equator) and can be used for multiple oxygen production processes (i.e., hydrogen reduction or carbothermal process), while other designs are much more specific. A Cassegrain concentrator system with an optical cable assembly, for example, could be placed anywhere on the Moon, while an offset parabolic concentrator using direct illumination could be designed specifically for operation on the South Pole (Refs. 9 and 16). It appears that a more highly modular concentrator design lowers the efficiency of the system; flexibility in design may be preferable or even necessary for specific missions and oxygen production rates.

Recent development of solar concentrators for both space and terrestrial applications along with development of oxygen production technologies has established the viability of producing oxygen from lunar resources. However, further development is needed for both concentrator and reactor technologies to enable successful operation on the lunar surface. Some of these developments would include: composites with a low CTE, high-strength, lightweight materials, materials able to withstand the harsh lunar environment, and highly-reflective coatings bonded to these advanced substrate materials.

More research needs to be conducted on the effects of lunar dust on concentrators. Plasma sprayers, compressed air, or simple window wipers are all being considered as dust mitigation alternatives for large mirror based concentrators. Integration of multiple concentrator technologies such as parabolic mirrors, secondary concentrators, heat pipes and fiber optic cables can be combined to provide a system that is optimized for a specific mission or task. It is entirely feasible, for example, to have a primary Cassegrain, a secondary concentrator, and a heat pipe working in conjunction to provide thermal energy to an oxygen production reactor. Each mission or application will require a unique technology solution that employs some combination of these technologies.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Oxygen production from lunar raw materials is critical for sustaining a manned lunar base but is very power intensive. Solar concentrators are a well-developed technology for harnessing the Sun’s energy to heat regolith to high temperatures (over 1375 K). The high temperature and potential material incompatibilities present numerous technical challenges. This study compares and contrasts different solar concentrator designs that have been developed, such as Cassegrains, offset parabolas, compound parabolic concentrators, and secondary concentrators. Differences between concentrators made from lenses and mirrors, and between rigid and flexible concentrators are also discussed. Possible substrate elements for a rigid mirror concentrator are selected and then compared, using the following (target) criteria: (low) coefficient of thermal expansion, (high) modulus of elasticity, and (low) density. Several potential lunar locations for solar concentrators are compared; environmental and processing-related challenges related to dust and optical surfaces are addressed. This brief technology survey examines various sources of thermal energy that can be utilized for materials processing on the lunar surface. These include heat from nuclear or electric sources and solar concentrators. Options for collecting and transporting thermal energy to processing reactors for each source are examined. Overall system requirements for each thermal source are compared and system limitations, such as maximum achievable temperature are discussed.

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