Power Architectures for Lunar Resource Development

Abstract: A study which explores the bootstrapping of power facilities required to support an emerging industrial base or a single facility. This includes considerations of siting, transmission, generation and distribution. Industrial, commercial and consumer applications are considered to provide a consistent front-to-back *review of the issues.*

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Energy requirements imposed on local spaceflight by gravity leads to an awareness of a very asymmetric relationship:

The Earth is close to the Moon,
and, *the Moon is a very long way from Earth.*

This realization tells us that applications in space are not about the flow of goods between space and earth. Viable applications are centered on services to Earth's inhabitants which result from hardware launched into various orbits from Earth. Examples of Earth-centric services which have developed into proven markets[1] are telecomm satellites, weather imaging and atmospheric measurement, solar monitoring, earth resources survey and national security. Some of these applications are profit centers for business while others remain imbedded within a non-profit governmental context, perhaps to be someday privatized.

Expansion of humankind into space is going to be dependent on *value-added* processes performed on raw materials located in space. The bulk of these materials will not have a *delta-V* applied to them before they are put to use as factories, foundries and housing for an indigenous Lunar Economy / Infrastructure. A small percentage of these materials will be exported to Earth orbits, LaGrangian Points, Venus, Mars, and Cycler Orbiters -- the remaining materials will be used to provide many of those Earth-centric services provided today entirely from Earth launch.

These space goods and earth-centric services will constitute the currency, lifeblood, the very *raison d'être* of Lunar Development. Until then the pioneering culture of space will countenance no waste and everything has value. Early on, each mission will attempt to build on the debris and the enduring accomplishments of previous missions.

Contemporary exploration scenarios for the Moon and Mars are increasingly dependent upon installation of prototypical industrial base to assure completion of the basic mission. Whether Oxygen on the Moon or Methane on Mars – astronauts will be expected to forage from their landing sites, install processing plants and rig storage facilities before their return ticket can be validated.

Since orbital velocities and gravity wells cause a terrific distortion of logisitics and economy, **power systems** should be built on the premise that they will be used for a specific project and then, at a later time, the system or its' components will be integrated into a larger grid.

SITING

The old bromide from the real estate folks about "location, location and location" has probably never been as *appropos* as in its' application to space. To the terrestrial concerns about location we must add delta vee, inclination and declination, orbital retrograde, *etc*. In the case of the Moon the most significant factors include Point-1-7 G and the 14-long days and nights.

An obvious way to build a full-time solar cell system is to install a power transmission line near the lunar equator and deploy fields of collectors at intervals along the right of way. The Lunar Diameter is 1738 Km (1080 miles) with a radius of 540 miles yielding a circumference of 3392 miles. At any given time an average of half of the system would be producing power.

Nearly every facility to be installed on the Moon will require a companion power plant of some type. Early installations will have a limited mission duration and their power facilities will be likewise constrained. It will not be long before higher capacity power plants will be installed to provide "power in the valley" or "on the mountain," to be shared by a varying mix of consumers.

Budgeting of electric power should always consider the costs of transmission. The positioning of electrical plant capacity on the Moon's surface may be the most important decisions shaping the future of Lunar development. They may further be the first large-scale civil engineering projects to be conducted on our neighbor's surface. The Lunar South Pole and Malapert Mountain complex would be a candidate for the first power plant and transmission lines to support exploitation of lunar water ice.

Initial power plants will be small and have characteristically short transmission line requirements. These early installations will then co-exist with evolving and larger powerplants, introducing large capacity, long-distance transmission requirements.

The grid will initially, and perhaps forever, be a bi-directional network where users may often be suppliers. Excess capacity at any given facility will, of necessity, be made available for consumption elsewhere on the grid. Generally, the larger the facility's plant, the lower the per-KiloWatt cost.

Any tendency to build larger, dispersed plant capacity will be offset by diverse industries co-locating in order to share precursor material, exchange of thermal capacities, manufacturing by-products, "settling ponds", and other industrial facilities enabled by the power plant.

TRANSMISSION

The web of wiring required to collect acres or miles of solar panels is lumped into the topic of "distribution." In our current context "transmission" describes long-distance, high-capacity electric power lines. These lines result when a collection of medium capacity plants or a single, high-capacity plant are connected to one or more high-demand consumers at a distance.

Practical considerations limit the available transmission media to a few:

- ✧ Microwave
- ✧ LASER
- ✧ Cable

which are reminiscent of the television media battles earthside.

The microwave and LASER links are limited to *line-of-sight* links. The proximity of the horizon means that most links will be short and the repeater count will be high. The ruggedness of the terrain adds to the design and operational complexity of these links although microwave and LASER links will often be able to "skip" over rough terrain.

Transmission by cable is the least exotic medium and one with which we have vast experience. The first question to be addressed here is the mode of operation, that is, will the grid employ direct current or alternating current? This is to revisit a controversy which raged at the end of the nineteenth century – should electric power be Direct or Alternating Current?

Direct Current

Since Direct Current (DC) is static it has only a potential difference and a constant polarity to offer to the grid. The latter can be a source of damaged equipment, such as automobile batteries, when the "jumper" cables are reversed!

Any DC transmission, whether measured in millimeters or miles, is dominated by Ohm's Law:

$$V = I \bullet R$$

where I is the current (in Amperes), R is the resistance (in Ohms) and V the potential difference (in Volts). An indispensible twin to Ohm's Law is Watt's Law:

$$P = V \bullet I$$

where P is power (in Watts).

Substituting Ohm's Law for the V term yields

$$P = I \bullet I \bullet R \text{ or } I^2 \bullet R$$

This expression quickly informs us that, to hold a constant current, as the length of a conductor (wire) grows the voltage has to be increased. The available DC voltage is rapidly lost, providing a practical limit of a few hundred feet for conveying power. The loss is dissipated as heat in the conductor.

Another DC transmission problem is that it offers only resistance as a voltage reduction method, which is entirely dissipative. To tap off a voltage lower than that presented on the cable a string of series resistors must dissipate power. There is no convenient way to increase the voltage or current downstream from the generators without introducing complex equipment.

Superconductive transmission lines are a special case of Direct Current which are very encouraging. Superconductors have no resistance to the flow of current, which takes the non-linear current bite out of the power I^2R product. A good superconductor can flow a loop of current indefinitely, even after the voltage source has been removed.

Superconductivity suffers from constraints which offer interesting limitations to its' routine implementation on Earth. Some of these constraints, ironically, are easily addressed in the harsh Lunar environment:

- direct current operation only
- a cryogenic operating temperature
- an excessive current demand collapses the superconductive effects
- any conflicting magnetic fields collapse superconductivity
- electro-magnetic pulses collapse superconductive effects

The moon may be particularly well suited for deploying segments of superconductive cable. The cable can be kept in permanent shadow, providing cryogenic temperatures associated with superconductivity, and at no cost beyond the original installation.

Superconductive cables will require magnetic shielding or conduit. The moon lacks an ionosphere or a magnetic field, further increasing vulnerability to solar activity and system-wide impulse.

A great advantage to superconductive DC is that unused current can be recirculated until a demand develops.

DC is appropriate to distribution webs but may not be so for long-distance transmission grids. Superconductive cable may be too exotic to implement during the bootstrapping phase.

Alternating Current

Alternating Current is dynamic in that it is always changing state, repeatedly cycling through three hundred and sixty degrees of rotation, generating sinewaves. When the alternators are held to a modest precision AC also serves as an intrinsic time base.

Alternating Current uses reactive components, in the form of transformers, to move voltage levels with modest dissipative losses. Additional features, such as varying current, isolation of power networks, *etc*. provide a much richer set of power solutions. The passive components employed have a low failure rate (high Mean Time Between Failure – MTBF), requiring very little servicing of the components.

AC offers reactance, both capacitive and inductive, as non-dissipative methods for stepping voltages up or down. There are resistive losses in reactive components but these are small when compared to the reactive effects.

The AC generators and transmission grid should implement a three-phase configuration (Δ - delta), referenced phase-to-phase with no neutral. AC is non-polarized, and many applications are phase insensitive as well.

AC operates at a higher efficiency than DC, and the higher the frequency the higher the efficiency. Conceptually DC is a special case of AC – a zero frequency case. Alternating Current has substantially lower transmission losses than DC.

Alternating Current is easier to filter than DC. Proper use of common and differential mode filters can effectively eliminate most transmission line noise without dissipating it wastefully as heat.

Selecting the operating frequency

Conventional 60 Hertz (or cycles per second) alternating current is the standard in North America. In Europe and in most other countries on the planet 50 Hertz prevails. In all cases the operating voltages are hugely inconsistent.

A feature common to both 50 and 60 Hertz line equipment is mass. The equipment is large in volume and materials required. Such excesses are impractical for transport to, and about the moon. A quick, *back-of-the-envelope*, check offers a more rational approach.

First we compute the angular velocity, ω, of a 60 Hz signal:

$$\omega = 2 \pi f$$

$$\omega = 2 \bullet 3.1415 f$$

$$\omega_{60} = 6.283 \bullet 60 \text{ Hz}$$

$$\omega_{60} = 376.99 = 377 \, \Omega \quad \text{(ohms)}$$

This is the same value as the impedance of free space[2] and had to be a compelling reason for the selection of 60 cycles per second for the Westinghouse alternating current frequency standard.

In aviation a different standard offers instruments and equipment with a much smaller and lighter aspect, all based upon an operating frequency of 400 Hz:

$$\omega = 2 \pi f$$

$$\omega_{400} = 6.283 \bullet 400 \text{ Hz}$$

$$\omega_{400} = 2513 \, \Omega \quad \text{(ohms)}$$

The 400 cycle reactance is higher than 60 cycle and comparing impedances yields a helpful ratio:

$$2513 / 377 = 6.665$$

The ratio of impedances of these two frequencies provides additional insight into implementation – 400 cycles will require *only 15% of the mass* that would be needed to implement 60 cycle infrastructure. The efficiency of operation can also be expected to be better than at 60 cycles, resulting in less dissipative loss (as heat).

Higher frequencies can be employed but have proven to be impractical when motors must be driven directly by the line to generate high torque. So 400 Hz has great potential.

GENERATION

Any comparison of the various power sources available for implementation on the Terran Moon would consider first the solar options. All solar options must consider the month-long day, with 14 Earth-days of day and night. This will always cut efficiency by 50% out of the gate, not counting the cycling of processes up and down.

> Less iron will be necessary were an Iron-only solution the only one. A 400 cycle transformer is 1/7th the mass of iron as a 60 cycle transformer of the same Wattage. The relatively small increment of frequency (from 60 to 400) creates possibilities for other materials as component options. Silicon and other "fillers" can be added and a 400 cycle toroid "sintered" from select metallic grains.

Batteries and Fuel Cells are storage devices, not power sources. They are useful as power sources during the "dark" part of the lunar day if they've been charged during the "day" by solar technologies. Batteries are not capable of generating power without prior charging.

Fuel Cells can deliver power indefinitely as long as there is an indefinite supply of hydrogen and oxygen. The biggest headache here is that hydrogen, in nearly every form, is very difficult to store. Container technologies may yet emerge which can solve this problem.

Solar cells are a low efficiency option which is a known technology now into a fifth or sixth generation. Simple in concept, solar cells require expansive tracts of real estate and are subject to abrasion and impact damage from meteoroids. Deployment and maintenance may well require on-site service.

The other solar options have much higher efficiencies and, as a result, require much less surface area for reflectors or focussing lenses. These options include fluid turbines, Stirling Engines, solar thermo-electric and thermionic conversion.

All of these options generate DC directly. The turbine and Stirling Engines may be equipped with an AC alternator instead of the DC generator. DC power sources can convert to AC through several methods, including inverters and DC motor / AC alternator units, but always at a significant loss of efficiency and expenditure of energy.

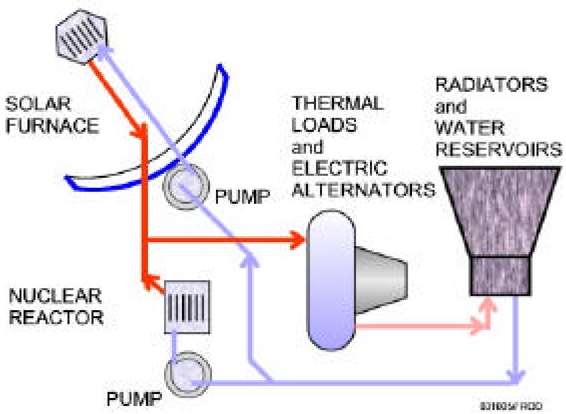

Figure 1. Nuclear / Solar Turbine Plant

The power sources which have r*ound-the-clock* availability are nuclear: thermo-electric, thermionic, turbines and Stirling Engines. These plants can deliver non-stop for six or more years and intermittently for many more years. The thermo-electric and thermionic units are strictly DC and the rotaries can be either DC or AC, depending upon the design.

A hybrid solution which can extend the service life of the nuclear fuel rods past ten years would be to bolt a solar turbine and nuclear turbine in tandem. While the nuclear reactor is shutdown during the "day" cycle it remains in the cooling path downstream from the turbine, allowing the reactor to maintain a shallow thermal cycle. The solar furnace alternates position in the plumbing with the reactor and actually radiates heat back into space when the reactor is online and the furnace is in the dark.

The hybrid solution is consistent with the notion that the endurance of a power generator must be long-term, or at least, a generator should be easily restarted.

Power Conditioning

Since the moon lacks magnetosphere and ionosphere it is susceptible to impinging electromagnetic fields from the sun and other sources. AC transmission lines can operate without shielding since filter circuits can be attached to the lines, thereby minimizing additional hardware like conduit or sheath.

A Common Mode filter has windings which are 180° *out-of-phase* and so cancels out noise which is "common" to both signal lines by applying the inverted signal into the true signal.

A Differential Mode filter has windings which are *in-phase* and so cancels out noise which "differs" between two signals, or that which is "unique" to either signal.

The *phase-to-phase* filter circuits will remove DC, surge and ringing from long distance transmission lines. These are sometimes generated when power is switched and "flyback" and other phenomenon are not properly handled.

The *phase-to-phase* filter circuits can also offer regenerative opportunities, gating the offending power events into storage capacitors. After the power has settled down an "inverter" can convert the captured energy to AC and re-apply it to the grid. Such a scheme may be implemented with a modest amount of hardware.

> The wavelength of a 60 Hz signal is 3104 statute miles or 4997 Km and a 400 Hz signal is 466 statute miles or 479 Km.

The long cables of the grid serve as an "antenna", absorbing electromagnetic energy with long wavelengths. The conventional solution is to attempt to block such signals or shunt them off of the grid. With regenerative filter circuits the "free" power available in space can be captured to supplement the power plants.

DISTRIBUTION

The costs of distribution are directly linked to the mass and complexity of translation hardware. The wiring costs will pale by comparison to the installed costs of DC converters.

The distribution grid must also be viewed symmetrically as a collection grid. With the preponderance of Solar Cells, Distribution and Collection will often be DC systems which will feature solid-state inverters and converters to change voltage levels. There are practical limitations to the size of DC function boxes, and DC will likely be relegated to local applications such as a solar cell "farm" or a launch rail.

The lower cost distribution technology would continue to be AC, unless DC devices must be connected.

BOOTSTRAPPING

Mission planners should avoid investing in sites which offer little for future operations to build upon. Locating power generators so as to minimize the requirements for installing follow-on transmission links is important in the synthesis of an infrastructural fabric.

A large number of power components use basic materials commonly found in Lunar Regolith. For the indefinite future those components which require trace elements, such as specialized semiconductors, can be economically supplied as finished goods from Terrestrial foundries.

The power solutions suggested here have the potential to employ a high content of value-added Lunar resources.

Lunar production capacity must include the masses of metal required for power generation, transmission and distribution, so as to avoid dominating the incipient production capacities with power infrastructure.

APPLICATIONS

All sorts of constraints and requirements show up when designers get to implement a system. Other application-specific concerns are listed here.

Power budgets should be 24/7 so that energy is not wasted on powering systems up and down in conjunction with the Lunar day. Thermal cycling of any technical or production equipment will only shrink the working MTBF and increase the demand for on-site service by human crew.

Standards will be necessary to assure seamless connection of each and every part of the power system. Having actual power utility companies in control of the grid's infrastructure is helpful in this regard.

Today's expediency (shortcut) becomes tomorrow's legacy, so don't install anything that you don't want to upgrade or cleanup later.

> Batteries suffer from a number of deficiencies which encourage other solutions for the lunar context. Batteries weigh too much, are easily damaged by freezing, have a short service life, and must be kept within a narrow storage temperature range and an even narrower operating temperature range.

One task which can be accomplished by robots is the installation of cable, whether on the surface or buried.

Power components which can be satisfied by value-added Lunar Regolith:

- solar panels – Silicon
- cables, wires – Copper, Aluminum
- toroids – Silicon, Iron
- transformers – Silicon, Iron, Nickel
- reactor coolant (NaK) – Sodium, Potassium
- conduit – Iron, Nickel, Aluminum
- film, plate – Iron, Nickel, Aluminum

Conclusion

The industrialization of the Moon will require development of an Alternating Current power infrastructure, possibly including power utility companies, nuclear reactors and transmission lines. Much of this infrastructure will be constructed from indigenous material, mostly Lunar Regolith.

[1] To begin to appreciate the actual extent of the existing application base (economy) please visit ***http://liftoff.msfc.nasa.gov/realtime/jtrack/3d/JTrack3D.html*** This site is subject to change but may show hundreds of satellites in LEO, MEO and GEO plus assorted strays in polar orbits. Hubble, Shuttle and ISS tracks are interesting to observe.

[2] *Chambers Dictionary of Electronics and Nucleonics*, Hughes, Stephens & Brown, compilers, Barnes & Noble, 1970, pg. 118.