Electrical Energy Storage Using Only Lunar Materials

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ABSTRACT

Lunar bases will need power storage systems for nightspan operations. In polar regions sun light is unavailable part of the time with darkness lasting for days at a time and in lower latitudes sunlight is unavailable 50% of the time. The lunar night lasts up to 354 hours. Night span power will be needed for communications, computers, lighting, physio-chemical life support systems and eventually for closed ecological life support systems at advanced bases. Gardens and algae tanks for CELSS illuminated by red and blue LEDs will require a constant supply of power. Mining and industrial activities will be suspended during night span to conserve stored power.

Of the various choices for energy storage, the Moon has all the materials needed to construct iron-nickel alkaline batteries – also known as Edison cells. These rugged batteries use nickel cathodes and iron anodes in an electrolyte of potassium hydroxide solution. Iron and nickel particles of meteoric origin are present everywhere on the Moon in the shallower layers of regolith and can be extracted magnetically. Potassium is present in lunar regolith and can be roasted out at temperatures over 900 C. Water is present in the ices of polar craters, and distributed across the polar regions. This moisture, or solar wind-implanted hydrogen, could be scavenged and combined with oxygen extracted from regolith. Containers for Fe-Ni alkaline batteries could be made of nickel plated iron or ceramics like cast basalt which resists caustic solutions of up to 30% concentration.

Iron-nickel batteries are very rugged. Their lifetimes which can exceed 20 years are not affected by heat, cold or deep cycling. They are not easily damaged by rapid discharging or over-charging. On the downside, they have poor performance at low temperatures but they can be kept warm with insulation (e.g. simple regolith) and thermal wadis. Also, they only have a charge to discharge efficiency of 65% and will self discharge at the rate of 20% to 40% per month. Despite these shortcomings, they might be the Moon-made power storage systems of choice due to their simplicity and the availability of their component materials on the Moon. Moreover, these materials are among the easiest of materials to produce on the Moon.

INTRODUCTION

Continually-manned lunar bases require nightspan power to sustain personnel. Several options are available, including: (1) a baseload nuclear power plant; (2) beamed power or reflected light from orbiting solar power satellites; or (3) energy storage from photovoltaics (PVs) installed at the base itself. Each approach has challenges in development costs, launch mass, complexity, and risk. A superior approach is to utilize in situ resources for option (3). Fabrication of PVs from lunar materials has already been studied [1]. In this paper we present a novel solution for nightspan energy storage which can be produced entirely from lunar materials.

Secondary batteries are those which can be re-charged. The first rechargeable battery, the same lead-acid technology used in most vehicles, was invented in 1859 by Plante in France. Forty two years later in the US, Thomas Edison invented a rechargeable iron-nickel alkaline (potassium hydroxide) battery which was sold continuously from 1903 to 1972 by the Edison Battery Storage Company. Improved secondary batteries eventually replaced the Edison cell, and on-going research continues the development of greater specific power (kWh/kg), longer charge retention, more cycles until failure (n), and the ability to deep cycle (discharging to a small fraction of the original charge) [2]. Today's batteries use elements like lithium and cadmium which are unavailable on the moon. Herein we re-examine Edison's simple and robust technology in light of in situ resource utilization (ISRU) approach to reduce launch mass for system power supportive of continuous occupancy of a lunar base. An additional constraint applied to this study is that the technologies employed all have dual uses in the construction or operation of the facility.

Materials needed to create an Edison cell are as follows: (a) iron for the anode; (b) nickel for the cathode; (c) water for the electrolyte; (d) potassium to make the water alkaline and conductive; and (e) a container. Secondary batteries employ reversible chemical reactions at the anode and cathode. The forward reaction (discharge) occurs spontaneously when a circuit is made between the electrodes. Loads in this circuit can draw power until the chemical reaction is used up, or the concentrations of byproducts inhibits further discharge. When PV power is available during dayspan, a portion of that power is applied in a reverse polarity to the battery. The chemical reaction is driven backwards, building up chemical potential in the cells. The half-reactions for discharge and recharge of the cathode and anode, plus the net reaction for the Edison cell are given in equation 1, where Fe is iron, Ni is nickel, H is hydrogen, O is oxygen, and e^- is an electron.

(1)

$$Fe + 2OH^- \Leftrightarrow Fe(OH)_2 + 2e^-$$

Iron-nickel fines are distributed across and within the lunar surface at concentrations of 0.1 to 0.5 percent. More iron is bound up in minerals, with the mare regions enriched compared to highlands, but on average lunar soil is about 13 percent iron. Nickel is less abundant, and averages 0.25 percent of lunar regolith, suggesting most of it is contained in the fines, and not in mineral form.

Water, or at least hydroxyl groups (OH), have been discovered on the moon, especially in polar regions. An Edison cell will require water to operate, but once sealed, this water remains, and does not need replenishment.

Potassium is available in concentrations of 0.07%, averaged between mare and highland soil samples from the Apollo missions. Potassium is found in the so-called KREEP materials, consisting of potassium (chemical symbol K), rare earth elements (REE), and phosphorus (P) at concentrations of 0.16% to 1.6%. Although KREEP terrains are richer in potassium, for this study, the average value will be used.

Containers for caustic potassium hydroxide (KOH) must withstand a 30% concentration. Cast basalt made from lunar maria regolith can withstand up to 50% KOH[3], making this an attractive and easily-fabricated selection for the container[4]. The same processes used to build cast basalt tiles, bricks, pipes, plumbing, roadways, landing pads, "igloos" and furniture at a lunar base can be employed to make the battery vessels.

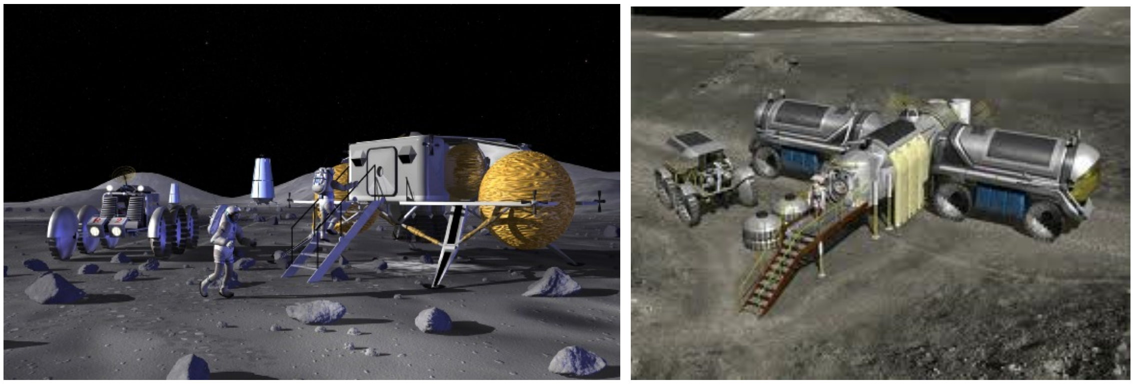

Figure 1. Two concepts for a lunar base sized for two people.

The base under consideration is a small one, designed to accommodate two people under the condition of a polar location where sunlight is available 85 percent of the time. Recent evidence shows locations at the south pole with up to 90% sunlight availability just 1 meter off the surface. When sunlight is unavailable, power-intensive operations will be suspended. This is perhaps the single drawback of stored power as compared to baseload power available from options (1) and (2) above. During this period of reduced activity, there must be sufficient power for life support, which includes horticulture, plus essentials such as heat, lighting, communications, and entertainment.

METHODS

A. Iron and Nickel Beneficiation

Meteoric particles of iron and nickel are found all over the surface of the moon, and can be harvested magnetically[5,6]. They contain about 5% nickel and are fused with silicate mineral grains. Centrifugal grinders can be used to break up the brittle silicates. This, combined with magnetic separation, can yield a 99% pure iron-nickel feedstock [7].

Separation of nickel from iron can be done with the carbonyl process invented by Ludwig Mond in 1890[8]. The Mond Process employs a warm (60 ^oC) vapor of carbon monoxide to produce a nickel-containing gas, called a carbonyl. The chemical reaction for this is shown in equation 2, where (s) indicates a solid and (g) indicates a gas.

(2) $$Ni(s) + 4CO(g) \rightarrow Ni(CO)_4(g)$$

If the nickel exists in an oxidized form, the addition of hydrogen is also required to liberate the oxygen. With the proper temperature and pressure, the Mond Process will selectively remove nickel from the FeNi particles, leaving reasonably pure iron behind. Nickel carbonyl gas can then be further heated in a second reactor to about 180 ^oC at which point the molecule decomposes, and pure nickel is precipitated. Alternatively, the Mond Process can be operated at a higher temperature, around 130 ^oC, at which temperature the iron also becomes a carbonyl. Through fractional distillation, the two gases can selectively decomposed to produce pure iron and pure nickel. Although simple, the Mond process has two drawbacks: first is the need for carbon, which only exists in parts-per-million quantities on the moon; and second, the carbonyl gases are highly toxic and pose a health risk to base personnel. Neither is insurmountable, since carbon compounds will exist at the base in the form of food, plants, body waste and cannibalized carbon composite and polymer parts from one-way cargo landers. Also, CO is needed only during the extraction and fabrication process and it can be recycled. Hazardous processes can be performed out of doors rather than within pressurized habitat where CO and/or carbonyl gases leaking from the equipment could be deadly, and the vacuum of space used to remove any residual gases. However, there are reasons to consider an alternate method for obtaining iron and nickel. Because iron is so plentiful in lunar minerals, an isotope separation process which processes both minerals and FeNi fines alike is an attractive option. A method of separation using high temperature plasma beam and separation by charge-to-mass ratio has been developed which is capable of extracting both elements simultaneously [5], [9] [10] [11] [12]. In fact, this process has a natural synergy with a novel means to extract oxygen, and the combination of these two manufactories has already been studied [13]. Effluent from this combined process is a refractory mineral slag composed primarily of calcia (CaO) and magnesia (MgO), which has a melting point (2572 ^{o}C) well above those of iron (1535 ^{o}C) and nickel (1453 ^{o}C). This slag can be formed into net shapes [9] [10] [11], and used for casting of iron and nickel electrodes. This process has the further advantage of being able to isolate potassium, as will be described in the next sub-section.

B. Battery Fabrication

The battery container can be formed by cast basalt, as described above. Iron-rich basalt is abundant in the mare regions, where is comprises the lava flows which form the dark "seas" of the moon's near side. With concentrated sunlight, or with electric heaters, or using electron beams, basalt can be re-melted, and cast to form the vessel and cap for the battery [14]. To make a sealed cell, necessary to retain water, lasers or concentrated sunlight can be used to weld the cap to the vessel. For polar regions where iron-rich basalts are uncommon, the vessel can be formed from CaO and MgO slag from isotope separation. When using slag, or other method of forming bricks or vessels, it may be prudent to upport polymer liners to contain the caustic.

Water will be obtained from polar ices and/or solar wind implanted hydrogen combined with oxygen. These operations require mining, manipulation, and heating of large masses of regolith. Because water is so valuable as a fuel source and for life support, we assume that the first lunar base will include capabilities to extract water.

Several methods to extract potassium exist. One method is vacuum roasting of regolith at between 900 and 1200 ^{o}C [15], under which conditions, about 30% of the potassium is released. This process is given further credence by the detection of potassium vapor in the rarified atmosphere of the moon[16], indicating that sunlight is sufficient to liberate at least some of this metal at the 130 ^{o}C peak surface temperatures of the moon. Trace amounts of sodium will also be liberated. Although sodium makes a good caustic, if its presence impairs battery function, these two metals can be separated by selective deposition, as their condensation temperatures differ by about 40 ^{o}C.

A second process by which potassium can be extracted is the isotope separation device described for obtaining iron and nickel. Figure 2 shows the amounts of potassium and calcium produced at various bins of charge/mass ratio, which bins are physically isolated collection receptacles. Calcium and potassium differ by a single proton, and both have several isotopes (numbers of neutrons), which overlap each other in atomic mass. Fortunately the primary isotope of potassium is its lightest, making it relatively easy to separate from the more abundant element of calcium. On the other side of potassium's charge/mass ratio is argon, which has not been found on the moon.

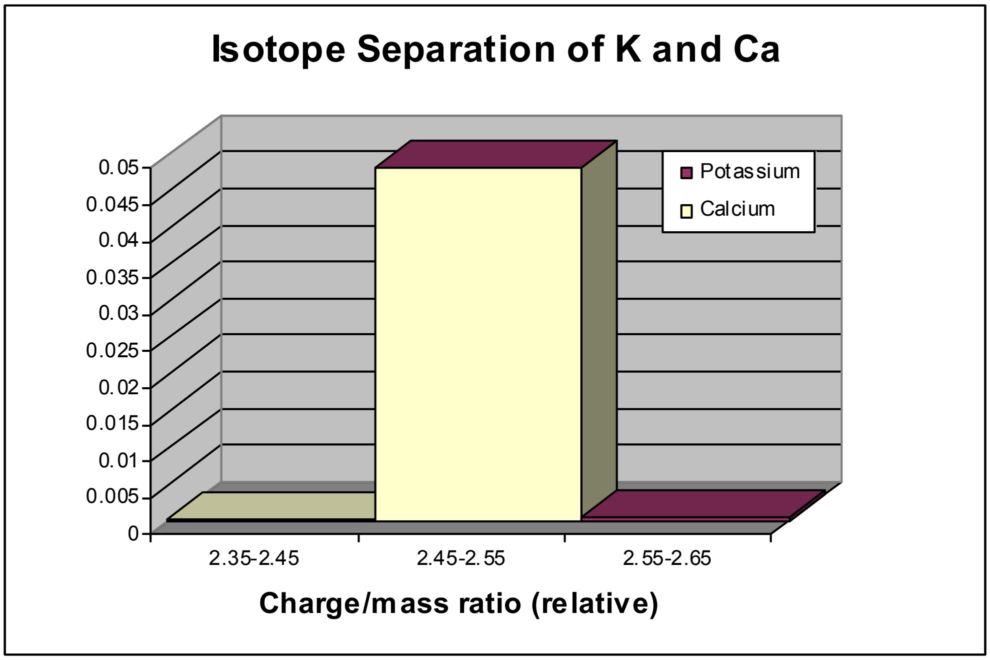

Figure 2. Isotope separation of potassium from calcium.

If the separation of K-39 from Ca-40 is imperfect, as might be expected due to beam width and velocity distribution, there is a fortuitous difference between these two elements. The solubility in water of K and Ca is vastly different, being 110 g/100 ml for KOH and only 0.17 g/100 ml for CaOH. Thus, the collected potassium, even if contaminated by calcium, will preferentially dissolve into the battery electrolyte, with a 99.8% separation efficiency.

The batteries are thus formed by creating a vessel, filling it with KOH electrolyte, immersing cast iron anodes and nickel electrodes, and welding a lid on the vessel to form a watertight seal. In practice, batteries are formed from the series connection of multiple individual electrochemical cells, each of which contributes 1.15 volts to the battery. A battery rated at 24 volts requires 21 cells connected anode to cathode.

If each battery is sized to hold 1 cubic meter of electrolyte with a specific gravity of 1.40, that mass is approximately 1.4 metric tons (MT). Electrode mass will depend on the thickness control of lunar casting, and is conservatively estimated to contribute another 0.5 tons. Specific power for an Edison Cell ranges from 0.03 to 0.05 kilowatt-hours per kilogram (kWh/kg), so this arrangement can be expected to hold a total amount of energy equal to about 76 kWh. Based on terrestrial designs, an Edison Battery has a deep cycling limit of 65%, so the available power during the lunar nightspan is about 50 kWh. Leakage of this battery technology is about 1 percent per day.

C. Siting and Temperature Control

Iron-nickel alkaline batteries must be protected away from freezing. Basalt casing is a reasonable insulator, but lunar nights near the poles can drop as low as -233 ^{o}C. Clearly, some amount of heating will be required. Vacuum is the best insulator. Assuming negligible heat conduction through feet under the battery, the R-value for vacuum is about 50 in units of meter-squared kelvins per watt. Taking a worst-case temperature outside (e.g. polar location), and a cell temperature of 0 ^{o}C (freezing for KOH is -28 ^{o}C), the heat flux from each face of the battery is -0.05 kW/m^2.

If all six sides are considered, with a nightspan time of 53.1 hours, the amount of energy required to keep the battery at that temperature is about 12.7 kWh. Factoring in self-discharge, this brings our estimate for a 1.9 MT all-ISRU Edison cell storage battery to 40 kWh.

D. Charging and Distribution

Figure 3 shows a schematic configuration for baseload power to a habitat using PVs and battery storage, including redundancy to protect against single-point failure modes. Two parallel PV arrays supply power during the lunar day, and also power their own heliostats for sun tracking. They are sized so there is sufficient excess power to charge the batteries for nightspan operation. The PVs are connected to the first Edison Battery through a circuit breaker. This battery is co-located at the PV array, and is redundant to the battery at the lunar base.

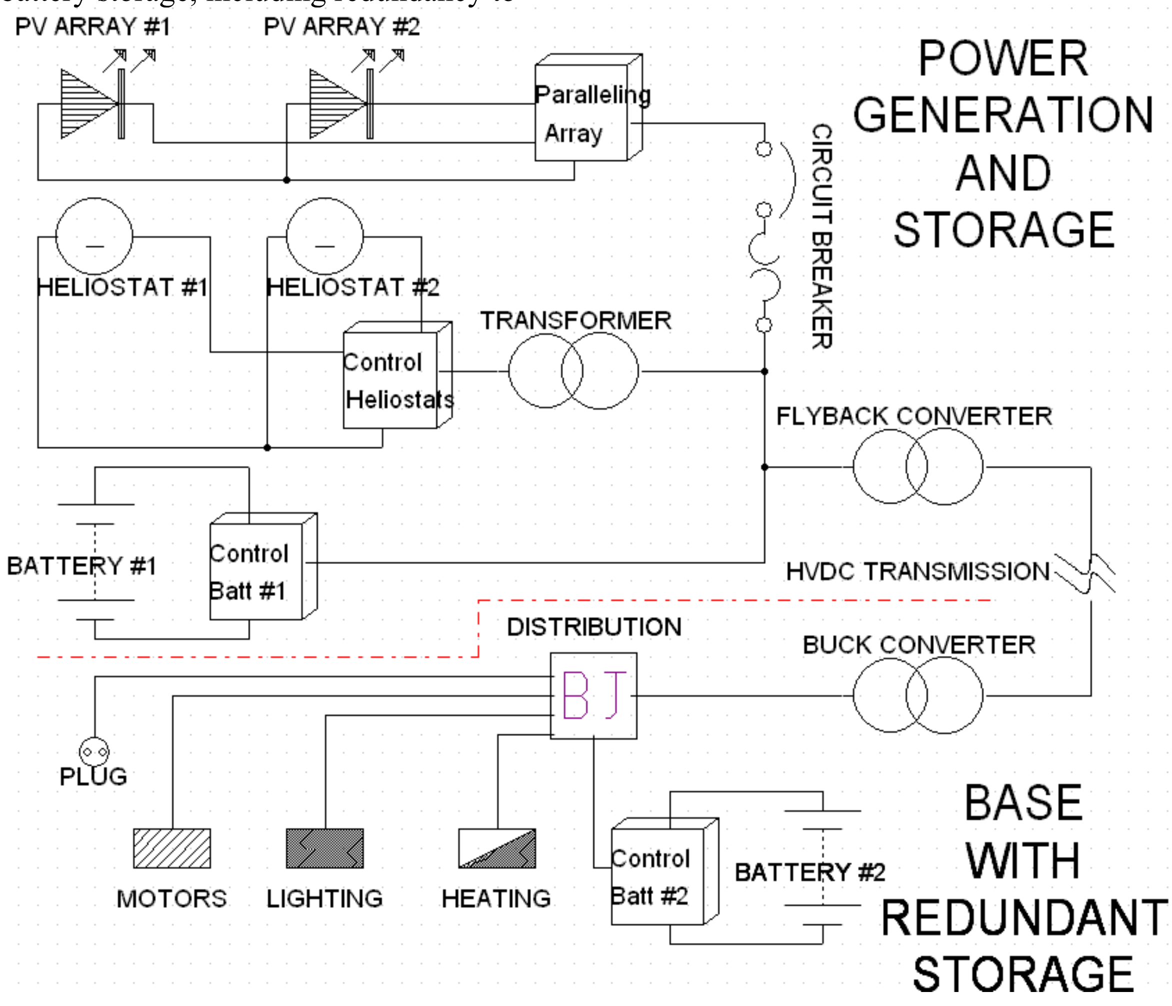

Figure 3. Power, energy storage, and distribution for a lunar base.

A flyback converter is a DC to DC transformer which can provide high voltage for transmission from the PV arrays to the base, which may be some distance away (e.g. at polar locations). A buck converter steps-down the voltage for distribution through a junction box at the base. The junction box (BJ in Figure 3) supplies power to the various needs of the base, and also provides re-charging power to battery #2. This arrangement provides for flexibility in the siting of the PV arrays (e.g. polar mountains) relative to the base, and provides redundant energy storage in two locations, so that a mishap at one site need not drain the base of a supply of power.

RESULTS

Horticulture requires light every day. Gardens and algae tanks can be illuminated efficiently by red and blue light emitting diodes (LEDs). Using data from conventional greenhouses, a 45 watt LED bank can illuminate a 0.46 m^2 area through the entire plant growth cycle.
Conventional electricity uses for an American household average 1.2 kW, and serve an average of 4 people. As a first order approximation, we can use this same value for non-heating uses in a lunar base serving 2 people. As another check, we can evaluate the silver-zinc batteries used in the extended duration LEM used on Apollo 15 through 17. These batteries stored 80 kWh of power for 2 men for 75 hours, or 1.07 kW. Given the close agreement between these two methods, we will use the higher power value hereafter.
Heating needs can be estimated by the same method used for battery temperature control above. Figuring on a habitat of 100 m^2 with a roof 3 meters high gives a surface area of 320 m^2.
Figuring a shirt-sleeve environment at 23 ^oC, and worst-case polar outside temperatures, the energy required to maintain heat is 678 kWh. This large number results from assuming the habitat is similar to those in Fig. 1, perched above the surface. However, given large scale excavations needed for lunar water, it seems reasonable to assume that the habitat could be buried under regolith. Lunar regolith is a good thermal insulator. At the lunar equator, sub-surface temperatures are about 23 ^oC if you bury yourself sufficiently. At 60 degrees latitude that drops to -24 ^oC. The average subsurface temperature near the poles (85 degrees and higher) would be below -110 ^oC [17]. Thus, depending on habitat configuration and latitude, energy for heating may vary between a very small number and 678 kWh.
Hydroponic gardens require about 20 m^2 per person to grow food. If we assume the greenhouse is half of the floorspace (50 m^2, so we generate a surplus), it will require 133 kWh. Household energy is 64 kWh. Grand total energy requirement is then 209 kWh, or a total of 6 batteries. With redundancy, this number is doubled to 12 for continuous occupancy of a polar base.

DISCUSSION

Power storage requirements are a sizeable fraction of the total mass of a lunar base using PV power. The 12 batteries needed for a 2 person base will require 12 MT of water and 6 MT of iron and nickel. Calculations of mass output for iron are approximately 16 MT per year with isotope separation [18], or covering 4.6 million m^2 using magnetic harvesting [5]. The time required, with one isotope separation unit (massing 1.3 MT) is then 5 months, or with magnetic harvesting is 1 to 2 months (massing 0.4 MT).
Based on dual-use principles, it may be desirable to employ both technologies described for metals production, since the isotope separation process also extracts potassium, aluminum (for wires), and silicon (for PVs); and a FeNi sweeper can provide metal building material for habitats, electromagnetic launchers, and rail lines.
Additional equipment needed to build Edison cells on the moon include water collecting equipment, and solar furnaces for processing basalt objects and smelting metals.
For a larger base, we can see that Biosphere 2 housed eight people and enclosed 3.15 acres of space. To illuminate this area for two weeks, about 437,000 kWh of energy or 2,000 batteries are needed at 40 kWhrs per battery. Even if batteries or fuel cells with ten times the specific power storage capacity were used the cost of shipping the required tonnages to the Moon would be prohibitive.

III. CONCLUSION

In this paper we have discussed, but have yet to develop, a means by which nightspan power needs for a small, continuously-occupied lunar polar base can be supplied using only lunar materials, and the factories needed for ISRU processing. The Edison cell technology, invented 109 years ago, is a robust technology with properties well-suited to this application. A realistic progression would be to land astronauts in earlier missions to set up the factories and robots until they are able to operate remotely or autonomously. Once the capability to withstand the lunar night is established, the robots and manufactories can be repurposed to other useful tasks, such as developing a circumpolar railroad where cars can follow the sun, and building ever-larger habitats to support a greater number and diversity of people and activities.

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