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Architecture for Developing an Economically Viable International, Large-Scale Lunar Colony*

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Abstract

Human lunar colonization has been studied at length, with the broad conclusion that it is technically feasible, but costs far too much. Even assuming a factor of 50 launch cost reduction, traditional models suggest that a lunar colony supporting 1,000 people would cost ~$4 trillion to develop, $100 billion to deliver, and >$6 billion/year to staff and supply. We estimate that an alternative architecture can create this 1,000 person lunar colony for a development cost of ~$2 billion, transportation cost of ~$5 billion, and annual support cost of $1 billion.

The approach proposed here builds on, but greatly extends the philosophical and technical approach (but not the technology) successfully adopted by the SmallSat community. The principal elements of this new architecture are: (1) work primarily indoors, rather than outdoors, (2) use existing, low-cost hardware, (3) use existing lunar resources (in a cost efficient fashion), and (4) engage multiple stakeholders in lunar development as participants, sponsors, and entrepreneurs. Individually, these elements have been identified in prior work. However, the proposed system architecture combines them for maximum impact on both cost and risk of development, transportation, and operations and creates an environment radically different than that previously envisioned.

The concepts of "smaller, faster, better" are, of course, relative terms. The fundamental question being addressed here is whether the low-cost methods that have been successfully applied to SmallSats can also be applied to inherently large and traditionally dramatically expensive missions. It is our conclusion that, with appropriate modifications, they can be. If it can be accomplished, there is far more to be gained by taking fundamentally large programs and making them "smaller, faster, better." Finally, the proposed approach is inherently international in its implementation and would involve participation by a large number of countries and organizations.

Introduction

The fundamental limitation to expansion into the solar system is not technological, but economic. It simply costs too much to create Moon colonies, send people to Mars, do manufacturing in space, or initiate space tourism. The problem is driven by launch costs, which have not changed substantially in 30 years. [Koelle, 1995; London, 1996]. As listed in Table 1, at least 10 organizations are in the process of developing technology with the objective of reducing launch costs by a factor of 5 to 100. However, even if these are successful, current mission cost models imply that this will not be sufficient to create economically viable large-scale space programs, such as a large lunar colony [Eckart, 1996a].

Table 1. Systems Currently Under Development Intended to Dramatically Reduce Launch Costs.

Organization	Launch Vehicle	Organization	Launch Vehicle
Boeing	Med-LITE	Boeing, Energiya	Sea Launch
EER Systems Corp.	Conestoga	Beal Aerospace	BA-2
Kelly Aerospace	Astroliner	Microcosm, Inc.	Scorpius
Kistler Aerospace	K-1	Rotary Rocket Co.	Proton
Pioneer Rocketplane	Pathfinder	Lockheed-Martin	X-33

The long-term high cost of launch has created a space paradigm that values technical optimization and systems engineering over simple, potentially low cost solutions. (See, for example, Larson and Wertz [1992], Griffin and

French [1991], or Shishko [1994].) For instance, space engineering standards would require Los Angeles traffic to be system engineered for optimal efficiency which would likely entail a fully automated automotive control system with cars and trucks driven remotely by a "Traffic Operations Control Center," with extensive software and multiple back-ups to avoid system failure. It is possible that such a system could reduce congestion and potentially postpone building new freeways. It is also possible that it would take years to analyze and design, cost a truly astounding amount to create, and might or might not be fully implementable or cost effective when complete.

In the space arena, a number of organizations have for many years, implemented a new, much simpler paradigm for space systems that has reduced mission life-cycle cost for "LightSats" by a factor of 2 to 10 over that anticipated by traditional cost models [Wertz and Larson, 1996; Sarsfield 1998; Bearden, *et al.*, 1998]. Unfortunately, many of the techniques employed are only applicable to small systems—e.g., have the space system built by a crew of no more than 20 people, use piggyback launches or "space available" rides, use existing spares or nearly free labor. Nonetheless, the broad philosophy and technical approach (trade on requirements, use non-space equipment, use commercial parts where appropriate, create a motivated crew) can be applicable to larger missions [Wertz, 1996].

A key question becomes: Could the technical and philosophical basis of LightSat systems be combined with other known approaches (e.g., use of indigenous resources) and launch cost reduction of an order of magnitude to create truly affordable large scale space missions. This was addressed by the author in a graduate course in *Low Cost Space Mission Design* at USC in the Spring, 1998 [Wertz, 1998]. Specifically, we addressed whether a near-term lunar colony with a population of 1,000 could be created for an affordable cost (i.e., one to two orders of magnitude less than the $4 trillion dollars estimated by Eckart's cost model). I believe that the fundamental answer is Yes.

Summary of Concept Design

As a baseline we assume a total factor of 50 reduction in launch cost. This is based on at least one of systems listed in Table 1 being able to reduce costs by a factor of 10 and an additional factor of 5 due to economies of scale associated with the need to put thousands of tons annually on the lunar surface. We next apply the "Traditional" Lunar Base Cost Model developed by Eckart [1996a]. The basic assumptions of the model are listed in Table 2 and the resulting cost baseline is shown in Table 3.

Table 2. Baseline "Traditional Low-Cost" Lunar Base Cost Model. Based on Eckart [1996a] plus a factor of 50 launch cost reduction. (See text for discussion.) LS = Lunar Surface

• **Transportation Cost** – Mass at LS is 5-10 times less than mass in LEO (assume 8x) – Current launch cost = $10K/kg to LEO = $80K/kg to LS – Factor of 50 cost reduction (see text) gives $1600/kg to LS = $725/lb = $1.6 M / metric ton
• **Other assumptions** – Eckart used crew of 8 with resupply from Earth being cheaper than production on LS – Baseline here uses Eckart model with "max. lunar base" with solar power, O_2 production, and closed-loop life support * Installation = 40 tons/person * Resupply = 3 tons/person/yr (based on Eckart crew exchange of 4 times/yr) * Develop. & Acquisition cost =$100K/kg with economies of scale(Eckart model=$100K/kg to $1,000K/kg)

Table 3. Results of Baseline Cost Model for a Large Lunar Colony.

NONRECURRING COST TO SET UP COLONY:

	Per Person	8 People	1000 People
Development and Acquisition	40t = $4B	320t = $32B	40,000t = $4,000B
Transportation Cost (low-cost)	$65 M	$500M	$65B

RECURRING ANNUAL COST TO MAINTAIN COLONY:

	Per Person	8 People	1000 People
Transportation Cost (re-supply and crew exchange every 3 months)	3t/yr = $5M/yr	24t = $40M/yr	3000t = $5B/yr
Personnel Cost			
On the Moon	$0.15M/yr	$1.2M/yr	$150M/yr
Earth Support	$0.75M/yr	$6M/yr	$750M/yr

SUMMARY: Using a factor of 50 reduction in launch cost, our 1,000 person colony would cost $4 trillion to create, $60 billion to get to the Moon, and $65 billion/yr to support. Not a winning scenario to present to Congress.

One of the key issues is the cost of personnel. The Eckart study and much of the prior NASA work have assumed primitive living conditions, such that the crew would be rotated out every 3 months. Figure 1, from a NASA Moon base study, is illustrative of the problem. Note that the working space is so confined that the person is kneeling for the entire time they are remotely operating the machinery. It is perhaps not as surprising that an artist would draw this, as it is that none of the technical personnel would object. Lunar colonies have been thought of as a "Space Station on the Moon" with small, connected modules typically brought from Earth. As shown in Figure 2, we envision something much closer to an O'Neil Space Colony on the Moon with a large interior volume built from local materials. The fundamental objective is to build an environment that is pleasant and spacious such that most work on the Moon could be done indoors and workers would come for an extended period. This dramatically reduces the "transportation tax" associated with getting workers to the Moon and, consequently, implies labor costs for work on the Moon at rates approximately 2 to 5 times that in the United States. Personnel transportation cost is summarized in Table 4.

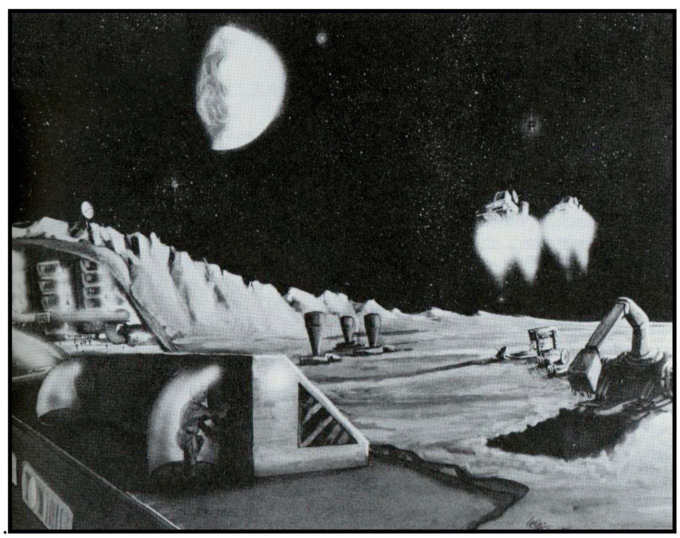

Figure 1. The Traditional NASA Style Lunar Colony is Fundamentally Hostile to People. Note the worker kneeling in the equipment control module with no room to stand.

Figure 2. A More User-Friendly Lunar Colony Based on O'Neil Style Space Colonies. Most of the day-to-day work (including construction of everything but the colonies themselves) can and should be done indoors.

Table 4. Transportation Cost by Personnel Class. Because of the high cost of transportation, computers, cameras, and personal items would be brought from Earth, while tables, chairs, buildings, and the basic colony structure would be built from indigenous material.

- Assume return cost = 25% of cost of getting there
  - $2000/kg round trip fare
- Transportation cost by personnel class (round-trip fare)
  - Tourist/visitor (economy class) = 150 kg on the Moon = $300K
  - Tourist/visitor (deluxe) = 250 kg on the Moon = $500K
  - Office worker/bureaucrat = 500 kg on the Moon = $1M
  - Construction worker/explorer = 1t – 2.5t on the Moon = $2M – $5M
  - Office/construction supplies are largely one-way
- Assume stays for workers range from 1 to 5 years, with a mean stay of 3 years. This implies an additional $10K to $30K per month per worker for transportation.
  - Implies labor costs on the Moon 2 to 5 times US labor costs

This leads to the obvious question, "What would everyone do on the Moon?" As shown in Table 5, with a population of only 1,000, there appear to be far more jobs than people available to do them. For example, if there are two representatives from each of the 50 countries, republics, or states with more than 15 million people (i.e., the size of the Netherlands or Texas), this would be 100 people whose major job is to ensure that there are regular broadcasts from the Moon in each of the world's major languages. Many people are likely to hold multiple jobs because of the high labor rates. Thus, the representative from Texas might broadcast to schools in native Texan during the day and open the first lunar chili parlor in the evening.

Table 5. Representative Lunar Jobs.

- **2 diplomats/representatives** from 50 countries, republics, or states with more than 15 million people (population of the Netherlands or Texas) = 100 people
- **Sciences**—astronomy, geology, biology, physics, chemistry
- **Engineering and technology**—materials, low-gravity construction, spacecraft design from lunar materials, launch and propulsion technologies; ultra-high and ultra-low temperature environments
- **Exploration**—scientific and commercial
- **Entertainment and arts**—sports, specials, educational TV (multi-lingual and multi-cultural), photography, art (static and performances), advertising and marketing
- **Construction**—building and maintaining new facilities for the Moon and space, roads, power lines, air lines
- **Utilities**—power, water, air
- **Infrastructure**—police, fire, medical, administrative, rescue, schools and child care
- **Food**—farming, markets, restaurants
- **Transportation**—on the Moon, Earth-Moon, asteroids and comets, elsewhere in the solar system; people and freight
- **Tourism**—hotels, tours, events, marketing
- **Manufacturing (internal consumption)**—construction materials (metals, glass, concrete), building supplies (windows, walls, furniture, household products)
- **Manufacturing for export**— structural components for space stations, satellites, and space vehicles; low-g and 0-g manufacturing, pharmaceuticals, semiconductors; vacuum and low-pressure manufacturing
- **Mining**—materials for lunar consumption, gemstones, minerals
- **Maintenance and repair**—applicable to nearly all products
- **Environmental science and engineering**—preservation of the lunar environment, monitoring and maintenance of the life-support environment, monitoring the solar-terrestrial environment
- **Retail sales and trades**—everything on the Moon gets reused or recycled

Who would pay for all of this? That is very much like asking what it cost to settle and run California—no one really knows, and no one cares. There will be hundreds of governments (diplomatic outposts, exploration, colonization, science, and prestige), companies (making profit from virtually any of the activities or simply doing them for advertising and prestige), and individuals (tourists, investors, explorers, and entrepreneurs). Some will make money, others won't. Table 6 shows some principal sources of income for the lunar colony as a whole. There are more than enough goods and services to support a thriving lunar economy.

Table 6. Principal Sources of Income for the Lunar Colony.

- **Resources**
  - For export—^{3}He, lunar materials, gems to Earth; water, power, metals to spacecraft
  - For lunar consumption—air, water, power, glass, metals, food
- **Manufacturing**
  - For export—space structures, 0-g or low-g products, pharmaceuticals, semiconductors
  - For lunar consumption—buildings, furniture, structures
- **Services**
  - Maintenance, repair, and servicing
  - Visitor support services (tourism, scientists, athletes, film crews)
  - Infrastructure services (fire, police, rescue, administration, medical, diplomats)
- **Science and Exploration**
  - Virtually all types of funded science activities or sale of data and results
- **Arts and Leisure Activities**
- **Farming, Food Production, Distribution, Restaurants**

Strategies to reduce cost are summarized in Table 7 and can be roughly divided into economic, technical, and systems issues. Most normal, Earth-based equipment, except for gasoline-powered engines, will work perfectly well indoors on the Moon. (Gasoline engines would also function, but gas would be a bit pricey (around \$3,999.99$^{9/10}$ per gallon during full Earth specials) and the exhaust unwelcome.) Nearly all products used inside can be COTS products brought directly from Earth and should work well as built. Most manufacturing, construction, maintenance, and repair work (including building buildings and fixing outdoor equipment) would be done inside the colony using normal COTS tools. It is certainly much more comfortable and less cumbersome to work indoors in a shirtsleeve environment than in spacesuits on the lunar surface. Transportation inside the colony is by foot, bicycle, electric carts, or electric cars as the colonies get larger.

Equipment for use outside can also be COTS products modified for use in a vacuum environment with lots of dust. * (On the other hand, there is no wind, rain, dew, ice storms, or hurricanes.) Transportation, lifting, and hauling equipment can be light-weight commercial vehicles refitted for electric operation and good conductive heat paths. As in most practical applications, there will be careful selection and compromises. Much of the outdoor equipment could be commercial electric-powered equipment intended for use inside buildings or in underground mining operations. One could also explore using underwater equipment on the lunar surface. Parts of the equipment, such as a simple, but heavy baseplate, alignment bench, or counterweights for a hoist might be removed before shipment and replaced with ones made from lunar materials.

Because of the high transportation cost, there will be a large rental business for both tourists and professional visitors. Both cameras and clothes (from Hollywood inspired MoonSuits to Bermuda shorts) could be rented to tourists. Professional broadcast equipment could be rented to event sponsors or scientists needing to record activity or conditions. If someone does bring equipment of any sort from Earth, a good option would be for a local entrepreneur to buy it from them for later use by others.

Similarly, the high transportation cost implies that recycling will be "in" on the Moon–either fix it, recycle it, use it for something else, or tear it down and start over. Lunar manufacturing would be limited to simple, structural products where the mass of the product far exceeds the mass of the equipment needed to produce it. However, this represents most of the more massive items -- the colony structure and shielding, walls, desks, tables, and chairs.

As summarized in Table 8, the biggest single problem we have identified to date is the lack of a good source of nitrogen on the Moon. Although a variety of long-term solutions are possible, we have chosen to resolve this in the near term by including a "nitrogen tax" in the non-recurring development cost of $1.3 billion. This also implies the Moon colony will need to put significant effort into not letting large quantities of air escape. Thus, for example, an air lock that is pumped down would be used rather than simply evacuating it to the outside.

Table 7. Summary of Lunar Colony Cost Reduction Strategies.

METHOD	COMMENTS
Economic:	
Cost Sharing	Countries—for politics, science, prestige, education Business—for-profit activities Business—for prestige or advertising Individual entrepreneurs and tourists
Income Generation	Many if not most of the activities can be run as for-profit businesses or as prestige-generating branches
Sale of Space Resources	Economic value of physical resources is almost incalculably large—energy, materials, processing environment
Technical:	
Use of Lunar Resources	H_2O, Al, O_2, silicates are readily available
Use of Normal Commercial Equipment	Except for gasoline-powered equipment, most commercial equipment will work perfectly indoors and will require some modification for use outdoors on the surface
Systems:	
Safety and Risk Mitigation	Safety comes largely from size and duplication of facilities; environment is harsh, but largely stable and benign; biggest hazards are fire and pollution
Operations	Key issue is for the colony to run itself; only "ground control" is what the individual home office or home government demands

* At the insistence of a thermal engineer in our group, the author ran a high speed electric drill inside a plastic bag for considerably longer than it would normally be used to establish that convection plays only a small part in cooling most electric hand tools.

Table 8. The Nitrogen Problem. This adds $1.3 billion to the nonrecurring development cost.

- Nitrogen is required for plant growth and makes up 80% of the Earth's atmosphere
- Unfortunately, air is remarkably heavy (~1 kg/m^3) and, at $1,600/kg, expensive to ship (irrespective of whether it's in gas, liquid, or solid form—the weight's the problem)
  - In most rooms, the air weighs more than the people
- Potential sources of nitrogen in large quantities:
  - Extraction by heating from the lunar soil
  - Brought from a carbonaceous chondrite asteroid—9% of all asteroids are of this type and typically have up 20% bound water and 6% organic matter (C, N, H)
  - Brought from one of the comets or gas giants (CH_4 and NH_3 atmospheres)
  - Brought from the Earth's surface
  - Scooped by satellite from the Earth's upper atmosphere
  - Recoverable byproduct from the air around goods and people brought to the Moon
- For working purposes we will assume a colony interior height of 35 m, composed of 3 psi O_2 and 3 psi N_2
  - Assume half the N_2 comes from the Earth's surface and half available elsewhere
  - Gives cost of N_2 of $5,000/$m^2$ of colony area

Table 9. Risk Mitigation and Safety. The lunar environment is harsh. On the other hand, solar flares are the only dangerous storms and nothing in the environment regards you as a potential lunch.

Risk Area	Mitigation
Radiation	– Provide mass equivalent of Earth's atmosphere in shielding (lunar soil) * More pressure from inside atmosphere than weight of soil – Adequate warning time for those on the surface to come inside
Asteroid Hit	– Danger no different than on Earth. Asteroid not slowed by the atmosphere and consequences of a direct or near-by hit are similar
Loss of Colony Atmosphere (leaks, meteoroids, door left open)	– Meteoroid stopped by regolith used for shielding – In a large volume (the colony) air loss is slow even through a large hole (allows time to find and fix the problem) * Need warning system to detect pressure loss * May want rubberized liner (like auto tires) * Seals for interior buildings plus oxygen available in many places
Loss of Air Supply on the Surface (leaks, mechanical problems, personnel lost or injured)	– While outside, maintain continuous communication with the colonies – Major roads have supply line with air, power, and communications – Carry back-up supplies of air, power, communications equip. – Similar to safety on ships
Lack of critical supplies or major catastrophe	– Biggest safety elements are multiple colonies, multiple transportation systems, multiple communications links (on the Moon and to Earth)
Fire and Pollution – the biggest threats	– Fire in any confined space is a problem * Oxygen control is key -- cut fire off, supply it to people – Biggest threat may be pollution since there is no ocean or atmosphere for dumping * Safety comes from careful monitoring and cleaning or replenishing as required

A summary of the results of our revised economic model is shown in Table 10. The biggest individual cost savings are from— 1) using predominantly normal Earth equipment in an indoors environment on the Moon, 2) using indigenous resources for most of the heavy structural materials, and 3) further reducing transportation cost by creating an environment in which people want to stay and work for an extended period. As a preliminary model we envision using two domes (for safety), each 400-m in diameter and 35 m high covered by 5 m of lunar soil. This gives about twice the living area per person available in San Francisco. We assume 350 people in construction and exploration jobs, each with 2.5 tons of equipment needed to be brought from Earth and 650 people in office jobs, each with 500 kg of equipment. We have also added 800 tons of miscellaneous "colony" equipment, such as air pumps and filters. All of the indoor equipment is COTS, possibly with minor modifications. Most of the outdoor equipment is COTS modified for electrical use in vacuum and the high dust environment.

Our colony for 1000 people on the Moon costs less than the International Space Station. Thus, it is clear that the results are inconsistent with essentially every aerospace cost model ever created. A key reason is that we have assumed a factor of 50 reduction in launch cost that we cannot guarantee. However, we have had to go far beyond reducing transportation cost. We have used normal Earth equipment to build the colony out of material largely available on the Moon. We are building ordinary stuff (desks, chairs, houses, and windows) for a land without storms and without the aid of "optimal engineering." Consider, for example, the probable cost of designing and building a chair for the Space Station. For us, the first chairs are either boxes or rocks brought in from outside and smoothed off a bit. We are indeed using the lessons from the LightSat community, substantially expanded to meet the requirements of larger scale programs. In our view, dramatic cost reduction comes not from technological miracles, but from changing the basic paradigm of how we work in space.

Table 10. The Revised Lunar Colony Cost Model. Assumes 350 people in construction and exploration and 650 people in "office" jobs.

NONRECURRING COST TO SET UP COLONY:

	Per Person Worker	Per Explorer	1000 People
Development and Acquisition	0.5t = \$0.5M	2.5t = \$2.5M	1200t = \$1.2B
Additional "colony" equipment			800t = \$0.8B
Transportation Cost (low-cost)	\$0.8M	\$4.0M	\$3.2B
Nitrogen tax (250,000 m^2 x \$5000)			\$1.3B

RECURRING ANNUAL COST TO MAINTAIN COLONY:

	Per Person Worker	Per Explorer	1000 People
Transportation Cost (re-supply & crew exchange every 3 years)	0.2t/yr = \$.3M/yr	1t = \$1.5M/yr	500t = \$.8B/yr
Personnel Cost— On the Moon	\$0.15M/yr	\$1.2M/yr	\$150M/yr

SUMMARY: Still using a factor of 50 reduction in launch cost, our 1000 person lunar colony now costs \$2 billion to create, \$4.5 billion to get to the Moon, and \$1 billion/yr to support, with no more than 10% from one company or country.

Conclusion

With traditional approaches, even a factor of 50 reduction in launch cost is insufficient to create an economically viable approach to lunar colonization. Even with this launch cost reduction, a baseline mission to create a 1000 person colony on the Moon costs on the order of \$4 trillion to create, \$65 billion to get to the Moon, and \$6 billion/year to support. Even if economies of scale drive down the acquisition cost by a factor of four, a \$1 trillion cost represents \$1 billion for each of the 1000 lunar colonists. Clearly with costs of that magnitude, it simply will not happen.

The alternative model developed here suggests that with the same factor of 50 launch cost reduction, the total project would be carried out for an acquisition cost of \$2 billion, \$4.5 billion for transportation, and \$1 billion/year for support. With funding from a wide variety of corporate and government sources (both international and US), the burden on any one organization becomes relatively modest by the standards of today's space programs.

What can create a difference of that magnitude? What is it that leads us to believe that costs of acquisition could be reduced 1000 fold? Of the cost reduction factors listed in Table 7, by far the most important is creating a colony large enough that most work on the Moon is done indoors rather than outdoors. In the traditional approach virtually every piece of equipment is designed specifically and uniquely for working on the lunar surface. But by working indoors, virtually any equipment intended for indoor work on Earth also works on the Moon. Instead of inventing an entirely new equipment infrastructure, we simply make use of what has already been invented, developed, and proved in practice here on Earth. It is both dramatically cheaper and far more reliable. Similarly, rather than invent all new equipment for the lunar surface, we make use of Earth equipment, modified as needed to work in vacuum (mostly by adding heat paths) and the dusty environment of the lunar surface.

The second major cost driver is to use existing lunar resources for those elements which are massive, but not particularly sophisticated to build -- i.e., the colonies themselves, radiation shielding, structural components, furniture, and, of course, lunar water and oxygen. Sophisticated equipment (such as tooling, PCs, electric carts, and personal supplies) will be transported from Earth, but these represent a relatively small fraction of the mass of the goods needed on the Moon.

Finally, with a distributed network of stakeholders, the cost is both spread among a larger group and actually reduced in some cases by the ability of entrepreneurs to generate goods and services, and, therefore, profit to justify corporate spending on lunar colonization. Thus, travelogues from the Moon would be broadcast in many languages (and paid for by governments fostering education in their language). Hotel chains would invest money to make money from lunar tourists. Sporting organizations would sell the rights to televise lunar sporting events. And many entrepreneurs would establish small businesses doing everything from searching for lunar minerals to repair shops, rental companies, and restaurants.

The Moon has nearly unlimited physical and "social" resources. North America was explored by the Europeans largely to try to bring back precious materials, but this exploration had an economic and social impact far greater than simply the gold in California. The key to lunar colonization, and to driving down costs, is largely to see the Moon not as a scientific outpost ("Antarctica in a vacuum"), but as a place with almost unlimited potential for truly unique contributions to science, culture, exploration, and exploitation of physical resources to be used in space and on Earth.

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