Mic23-0100-3C

USC ASTE 523, Spring 2023

Design of Low-Cost Space Missions

**Why Aren't
We There Yet?**

A Near-Term, Income-Generating, Lunar Settlement

Part 3

Living on the Moon in the next decade

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Background – Why Aren't We There Yet?

- **Why aren't we there yet?**
  - There have been numerous papers and organizations devoted to building colonies and settlements on the Moon, Mars, and other planets
  - Dr. Gerard O'Neill and his colleagues started at Princeton, held some 15 conferences, with roughly 1000 professional papers, and formed the Space Studies Institute, largely to promote the colonization of space itself
  - Why have we not built settlements on the Moon or planets? Why has this been so hard?

- **Landing people on the Moon within a decade of the first manned flight was largely a political battle for technology supremacy between the United States and the Soviet Union**
  - The Apollo program cost about $250 billion (~$20B/person) in 2020 dollars
  - The final 3 Apollo flights were canceled to reduce cost

- **The Artemis program will land people on the Moon at the rate of ~1 flight/year**
  - Typical stay on the Moon will be about 2 months

To build a real lunar settlement we need both motivation for those involved (the government, the organizations, and the people) and the money to make it happen. In a traditional model it simply isn't worth the cost !!

TOPICS

- Objectives, Ground Rules, and Assumptions
- Traditional Cost Model
- Mission Objectives Revisited
- Bottom Line of Settling the Moon
- Cost Reduction (more in later briefing)
- What's the Lunar Colony Like?
- Some Income Sources (more in later briefing)
- Economic Justification
- "New" vs. Traditional Cost Model
- Does It Make Sense?
- Back-Up Data

Objectives, Ground Rules, and Assumptions

- **Basic Objective:**

  Create a model of a growing lunar colony supporting whatever facets of human activity — exploration, science, entertainment, etc. — that are worth the cost. Base the cost assumptions on a colony of ~1,000 people. Determine if such a colony is economically realistic.

- **Ground Rules and Assumptions:**

  — Assume a "standard of living" on the Moon approximately equal to what it is on Earth — private living, open spaces, trees, butterflies, cats, and squirrels

  — Assume current technology or whatever can be expected within 5–10 years

  — Assume total factor of 50 reduction in launch costs

    - Factor of 10 launch cost reduction via one or more of the methods now being considered (RLV, low-cost ELV, new technology, or a combination)
    - Additional factor of 5 reduction due to economies of scale (lots of flights)

  — For simplicity, work in current year dollars and assume all labor at a burdened rate of $150K/person year

  — Assume it's <u>not</u> economically feasible with current cost models — i.e., we need to be aggressive about reducing cost (We'll verify this assumption.)

Our fundamental questions are: "Is a large-scale manned lunar colony economically feasible? If so, how would we go about creating it?"

Basic Cost Model Assumptions

- **Transportation Cost is Critical**
  - — Mass at lunar surface is 5–10 times more expansive than mass in LEO (assume factor of 8 average)
  - — Current LEO cost = $10K/kg to LEO = $80K/kg to the Moon
  - — Assumed cost (high launch rates only) = $200/kg to LEO = $1.6K/kg to \Moon
  - — Cost of "low-cost" lunar transportation (factor of 50 cost reduction) =
    $1,600/kg = $725/lb. = $45/oz. = $1.6 million/ton (metric ton)
- **Use Peter Eckart's PhD Dissertation as an Unbiased Baseline Cost Model**
  - — Eckart typically assumed a crew of 8 people and found that resupply from Earth was more efficient than in situ production (O_2, food, etc.)
  - — We will use Eckart model with maximum lunar base in the polar regions using solar power, O_2 production system, and closed-loop life support
    - A lunar settlement would be far too expensive to be practical in Eckart's base model
    - Installation mass = 40 tons/person
    - Resupply mass = 3 tons/person/year (Based on Eckart's crew exchange rate of 4 times/year)
    - Eckart assumes development and acquisition cost of $100K/kg to $1,000K/kg, so we will use baseline cost of $100K/kg for development and acquisition, assuming some economies of scale

Using a Traditional Approach, even with 50 times lower transportation cost, is far too expensive

- **Non-Recurring Cost to Set Up the Settlement:**

	Per Person	8 People	1,000 People
Development & Acquisition	40t = $4B	320t = $32B	42,000t = $4,000B
Transportation Cost (low-cost)	$65M	$500M	$65B

IT'S THE COST OF THE STUFF THAT NOW DRIVES THE COST OF THE SETTLE3MENT.

- **Recurring Annual Cost to Maintain the Settlement :**

	Per Person	8 People	1,000 People
Transportation Cost (resupply & crew exchange every 3 months)	3t = $5M/yr	24t = $40M/yr	3,000t = $5B/yr
Personnel Cost			
On the Moon	$0.15M/yr	$1.2M/yr	$150M/yr
Earth Support (Crew × 5)	$0.75M/yr	$6M/yr	$750M/yr

BOTTOM LINE: **Even with a factor of 50 reduction in launch cost, our 1,000-person lunar settlement would cost $4 trillion to create, $60 billion to get to the Moon, and $6 billion/yr to support. Not a winning scenario to present to Congress, especially while people are talking about cutting Medicare and Social Security and recovering from storms and natural disasters.**

Mission Economic Objectives

- Focus first on personnel costs as a means of setting economic goals
- Assume return cost = 25% of cost of getting there
  - — $2,000/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

Our new objective is to create a viable mission model with labor rates on the Moon with labor rates on the Moon 2 to 5 times those in the US.

Rethinking the Bottom Line

- It's been over 50 years since Apollo, and human settlement of the Moon is still a ways off
- If we're going to create near-term lunar settlements, <u>something</u> has to change dramatically
- That "something" is really three things -- the basic motivation for doing it, the cost of transportation to get there, and the process of creating a settlement. Specifically,

I believe that you can make $100 billion/year (and likely much more) in the near term living and working on the Moon – and you can do it with components largely built on the Moon or normal commercial stuff brought from Earth.

- Profit shouldn't be the only objective, of course, but using it as the driving force allows other objectives to be met better, faster, and easier
  - In some ways it's similar on a much smaller scale to how the gold rush brought 300,000 people to California

Background

- I have taught "The Design of Low-Cost Space Missions" at USC since 1999.
  - As a result of the course, I've developed a collection of several hundred specific methods for mission cost reduction
  - The course is meant to be practical rather than theoretical, so most of the methods are based on relatively small LEO satellites because this is where most of the data and relevant experience are
- The question arose—Do these methods apply to large missions as well?
  - To answer this, we began looking at cost reduction for an inherently large mission—a lunar colony with 1,000 people or more
  - As you would expect, some methods apply and some don't. That's a discussion that takes more time than we have here, but will tackle later
- We'll discuss 3 key methods of reducing cost:
  1. Dramatically reduce the cost of transportation to and from the Moon (a lot easier than I first anticipated)
  2. Do most of the work on the Moon inside in a "normal" environment using everyday equipment
  3. Find ways to generate income living and working on the Moon

To create a real, successful, near-term lunar settlement, we're going to have to BOTH dramatically reduce cost with respect to traditional programs and find ways to use the settlement to generate very large amounts of $$$.

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Cost Reduction Method 1 – Reduce Transportation Cost and its Impact on Lunar Economics

- **Transportation cost is critical, but not the most important factor**
  - **Cost to go the Moon is ~8 times the cost to LEO or ~$80,000/kg**
    - **Using O_2 from the lunar regolith can reduce this by a factor of ~6**
  - **300 launches/year contributes an additional factor of 3 cost reduction due to economies of scale (using a 90% learning curve)**
  - **Need factor of ~3 "inherent" launch cost reduction**
    - **Possible sources: Air launch, reusable vehicle, low-cost expendable**
  - **Assumed cost of "low-cost" lunar transportation (total factor of 50 cost reduction) = $1,600/kg = $725/lb = $45/oz = $1.6 million/metric ton**
- **Use Peter Eckart's PhD Dissertation as an Unbiased Baseline Cost Model**
  - **We will use the Eckart model with maximum lunar base in the polar regions using solar power, oxygen production, and closed-loop life support**
    - **Installation mass = 40 tons/person**
    - **Resupply mass = 3 tons/person/year (Based on Eckart's crew exchange rate of 4 times/year)**
    - **Eckart assumes development and acquisition cost of $100K/kg to $1,000K/kg, so we will use baseline cost of $100K/kg for development and acquisition, assuming some economies of scale**

Economic Objectives for a Realistic, Near-Term Low-Cost Lunar Settlement

- **Focus first on personnel costs as a means of setting economic goals**
- **Assume return cost = 25% of cost of getting there**
  - **$2,000/kg round trip fare**
- **Round-Trip Air Fare (*Rocket Fare*??) by personnel class:**
  - **Tourist/visitor (economy class) = 150 kg on the Moon = $300K**
  - **Tourist/visitor (first class) = 250 kg on the Moon = $500K**
  - **Office worker/bureaucrat = 500 kg on the Moon = $1M**
  - **Construction worker/explorer = 1ton–2.5tons 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**

To be economically self-sustaining, we have to create a lunar colony that generates more income than it costs with labor rates on the Moon 2 to 5 times those in the US.

Cost Reduction Method 2 – Work Primarily Indoors

- **<u>Most important for real cost reduction: work primarily inside, rather than outside</u>**
  - **Make the indoor space big enough to house most of the day-to-day activities**
  - **Means that nearly all Earth-based equipment can be used on the Moon**
    - **Electric vehicles and equipment**
    - **Equipment built for homes, offices, factories, and repair shops**
  - **Principal exception is <u>no</u> gasoline powered equipment**
    - **Gas sells for $\$3{,}999.99^{9}/_{10}$ per gallon and up**
    - **Pollution bothers the neighbors**
- **Working indoors enables the real cost saver—Use existing commercial/industrial/consumer hardware and software**
  - **Reduces procurement cost by a factor of 100 to >1000 (may get a lot for free – "Sammy's Golf Carts, as used on the Moon")**
  - **Greatly improved reliability, spare parts, manuals, and user experience (manuals and repair instructions available on the internet)**
  - **May be able to use much of the commercial equipment outside as well**
    - **Modify for use in vacuum (good heat conduction paths added) and a dusty environment**

Don't reinvent the wheel, the bicycle, the electric car, or the iphone.

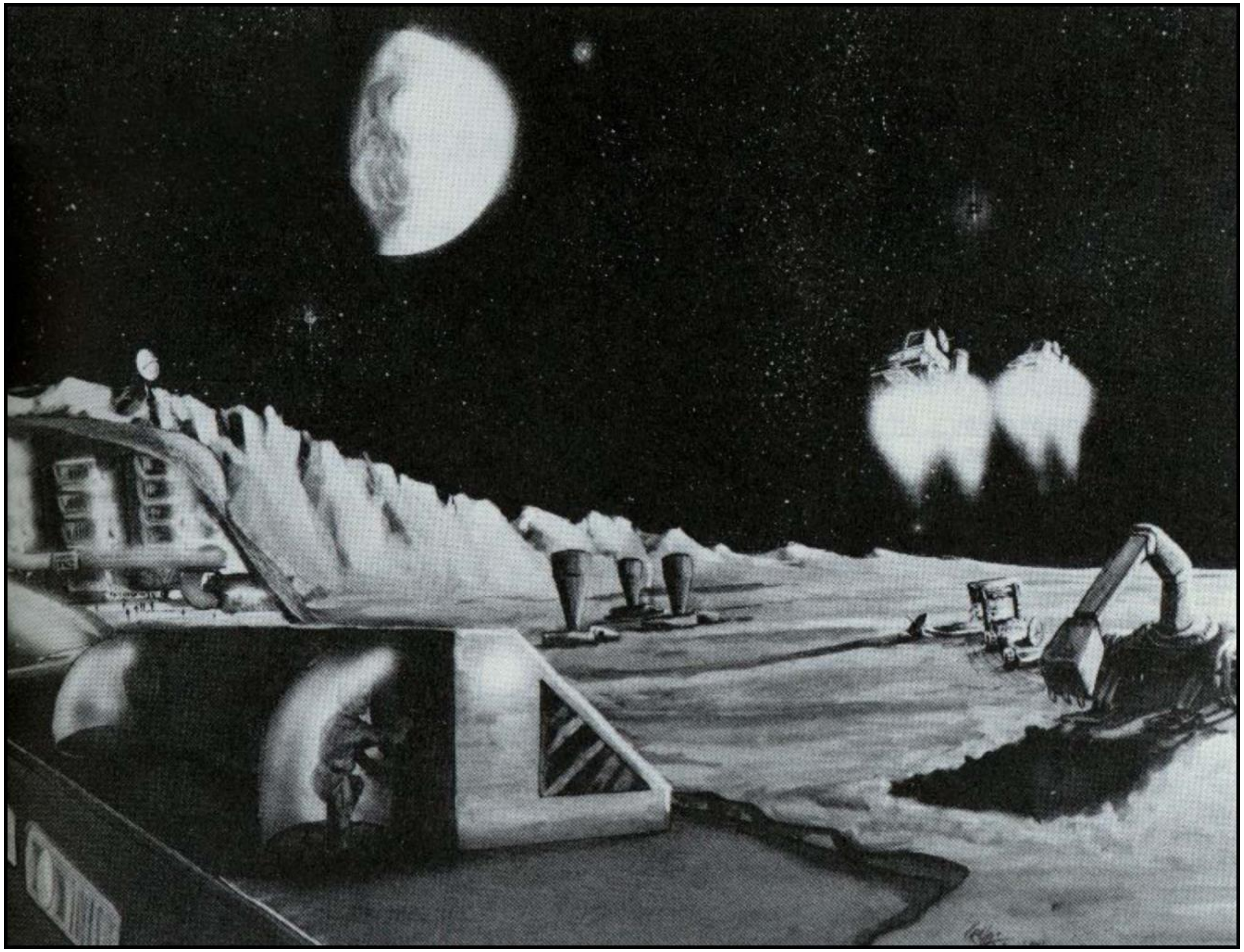
Related Cost-Reduction Techniques

- **Use existing lunar resources in a cost-effective fashion, not for anything complex**
  - Use lunar material for massive, simple structures and objects
    - The settlement structure itself— structure (aluminum & glass) and radiation shielding (regolith)
    - Walls, desks, tables, chairs, bookcases
  - Use lunar H_2O and O_2 — sadly, lunar settlement may need to import lots of N_2
  - Anything complex is bought commercially and brought from Earth
    - Machinery, office equipment, clothes, computers, iPhones, and electronics
- **Share the cost by engaging multiple stakeholders, sponsors, and entrepreneurs**
  - Many reasons for funding—national pride, education, science, exploration, settlement, advertising, personal adventure, and profit—lots of it
  - Some businesses will grow and prosper, others won't, and that's OK
  - **Principal requirement for financial success is to be able to support workers (or yourself) with a labor rate 2 to 5 times that in the US**
    - High, but not insurmountable, cost for countries, companies, and many individuals

In this model, lunar colonization is much more like settling California than building the International Space Station.

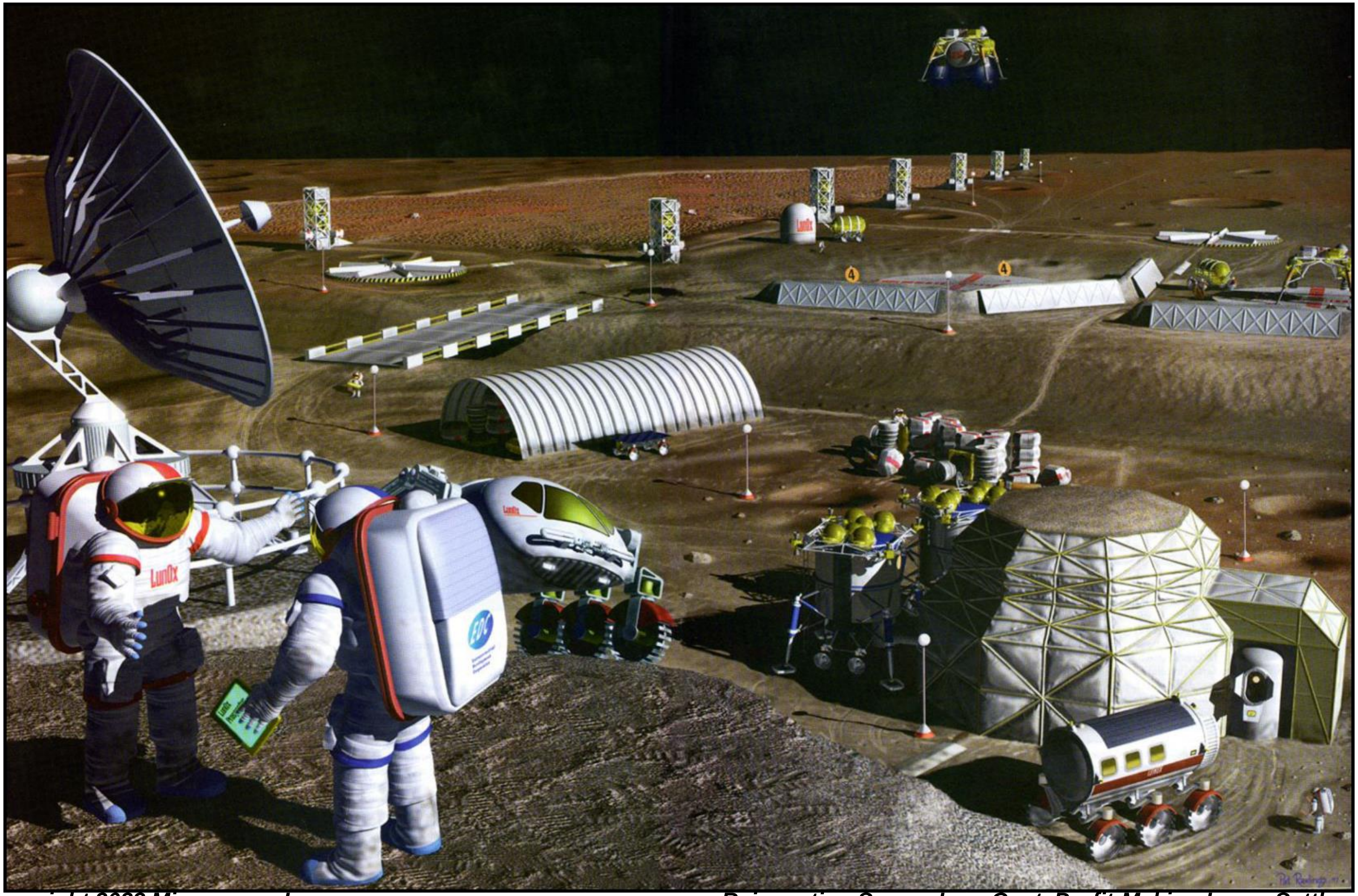
The traditional Lunar Colony is Fundamentally Hostile to People

- Note worker kneeling in the equipment control module with no room to stand



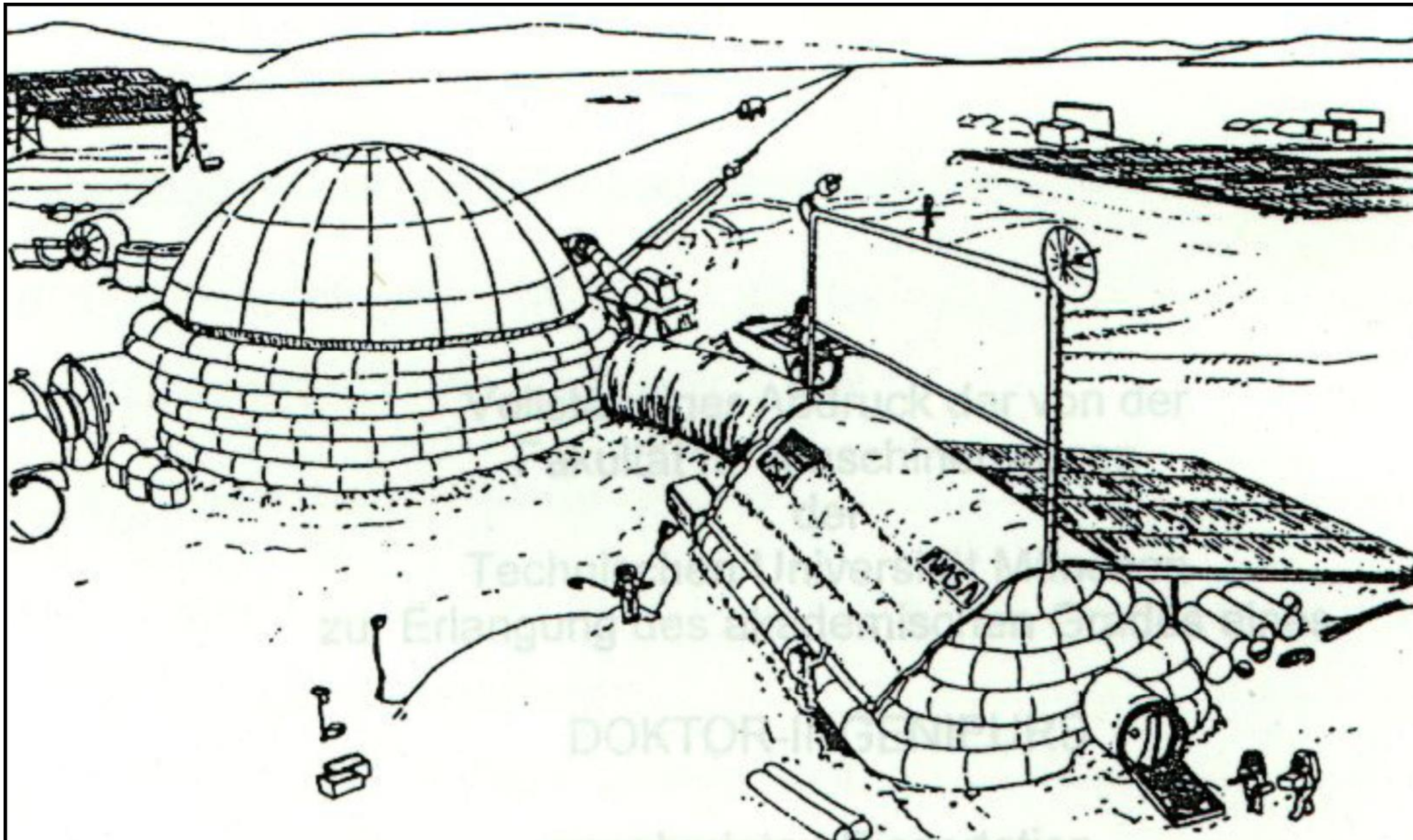
In the traditional Lunar Colony Most Work is Done Outside

Note: (A) The 6-wheel "lunar vehicles," (B) the open Quonset hut still requiring a space suit, and (C) the small living space without windows for a relatively large crew.



Lunar Colony Envisioned by Eckart Model

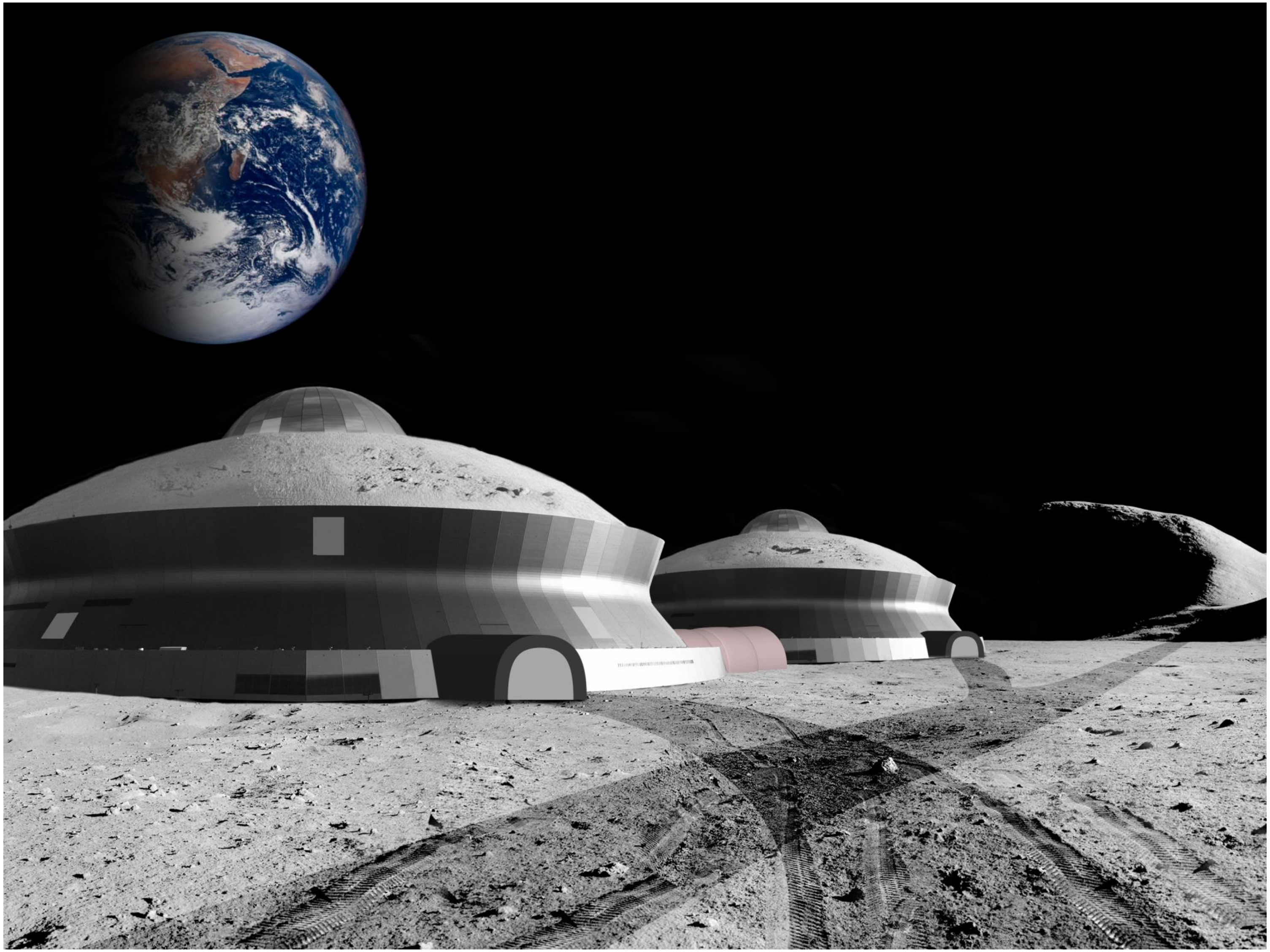
- **In Eckart's model, the conditions are sufficiently harsh that stays are limited to 3 months (crew rotation 4 times per year)**



What Should a Lunar Colony or Settlement Really Look Like? What Will It Cost?

- Physical structure = 2 (or 3) domes for safety, each 400 m in diameter, 35 m high covered by 5 m of lunar soil for radiation and meteoroid protection; total area in 2 domes of 250,000 m^2
  - — In English units, each colony is 1,200 ft in diameter, 110 ft (11 stories) high, with 15 ft of soil on top
  - — Each dome is the size of two 100,000 seat football stadiums and provides the housing and working environment for 500 people
  - — About twice the area per person available in San Francisco
- Permanent population of 1,000 people (and growing)
  - — 350 people in construction and exploration jobs with 2.5 tons of equipment each
  - — 650 people in office jobs with 500 kg (1,100 lb) of equipment each
    - — Not a lot of paper—the paperless office is "in" on the Moon
  - — Add 800 tons of miscellaneous "colony" equipment
- Equipment acquisition at $1,000/kg (approx. cost of portable PCs or airplanes)
  - — All indoor equipment is COTS, possibly with minor modifications
  - — Most outdoor equipment is COTS modified for electrical use in vacuum, high dust environment, and an air-tight compartment for people

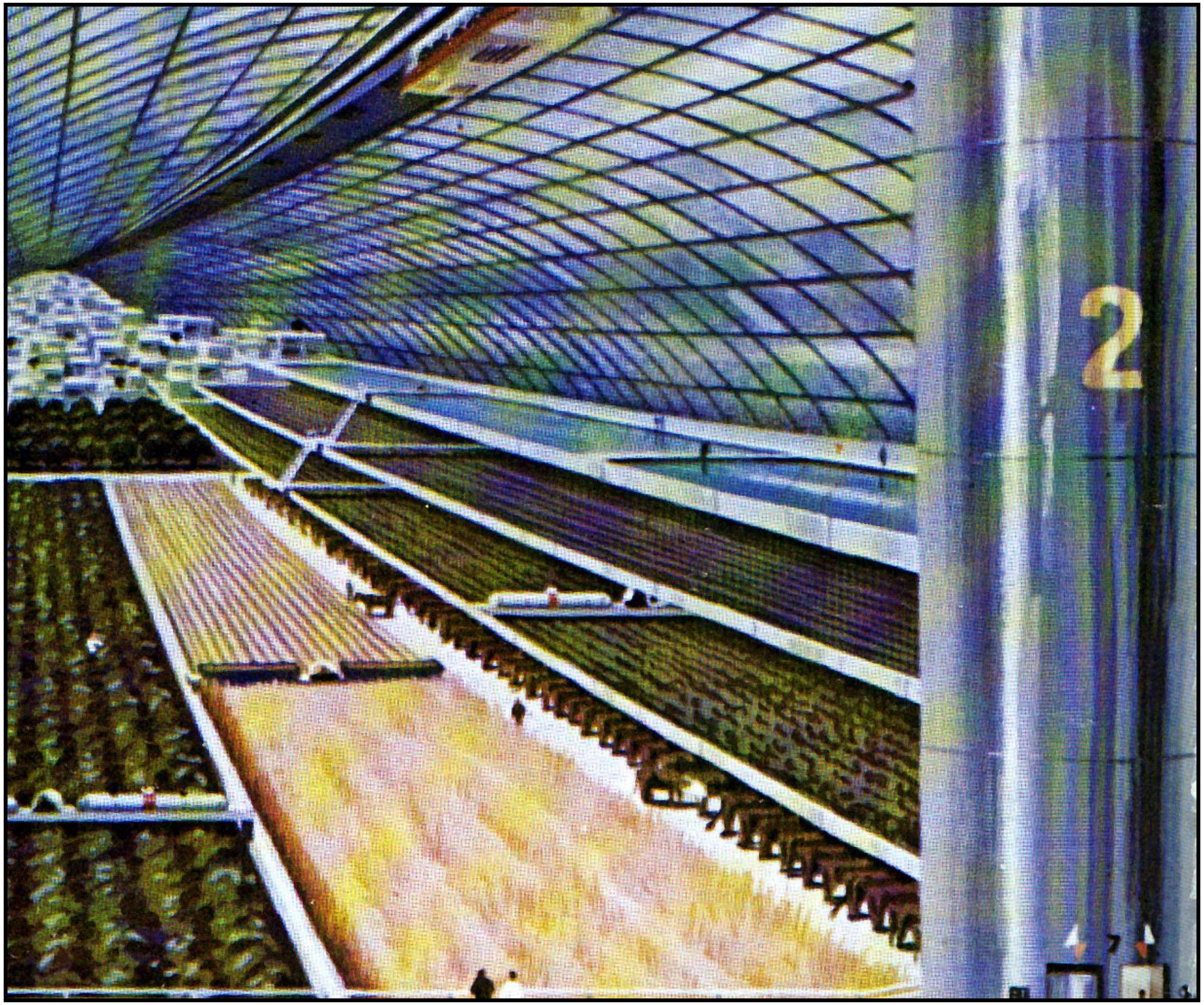
Representative Lunar Settlement --each Dome has Twice the Area of a 100,000-person sports stadium



Interior of a more People-Friendly Lunar Settlement based on O'Neill Style Space Colonies

- **Most of the day-to-day work (including construction of everything but the colonies themselves) can and should be done indoors**
- **Reasonable comfort is critical for long-term living—trees, birds, squirrels, and ponds**
- **Curvature in the picture is due to the form of O'Neill colonies—the lunar colony would be flat**

Representative Food Production Region



Preliminary Analysis of Income Sources

This is a good area for Final Reports

- **Lunar tourism provides the high level of transportation and activity that enables other missions at low cost**
  - ~7,000 tourist trips/year and growing when the colony reaches 1,000 residents (for comparison, annual visitors are 1,500,000 for Guam and 70,000 for American Samoa)
  - Tourism + lunar burial provide the basis for getting underway ($7.5B – $24B/yr)
- **Co-branding is likely the largest income generator and doesn't require any specific activity on the Moon ($85B – $560B)**
- The other major longer-term income source appears to be energy for Earth [^{3}He or Solar Power Satellites (SPS) or both]
  - ^{3}He + SPS gives total lunar income of $50B to $170B/year
  - Only 1 of the 2 power sources gives total lunar income of $17B to $90B/year
- Don't yet have a good understanding of some of the other sources of income (and their cost), such as entertainment and the arts, mining, or knowledge preservation

A key issue for the development of the lunar colony is a more detailed economic analysis of both costs and income from multiple sources.

The Co-Branding/Advertising Industry is Likely the Largest Revenue Source

- **Co-Branding Definition:**

  Selling co-branded goods with a lunar brand and paying a license fee to the lunar business or lunar colony for each sale

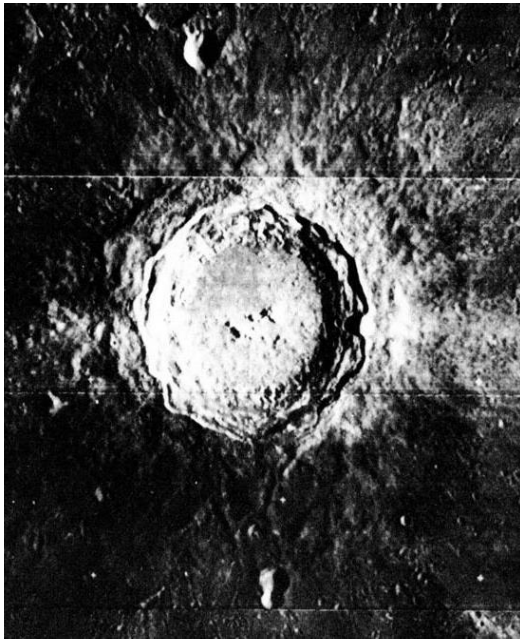
- **Brand Value Estimation:**

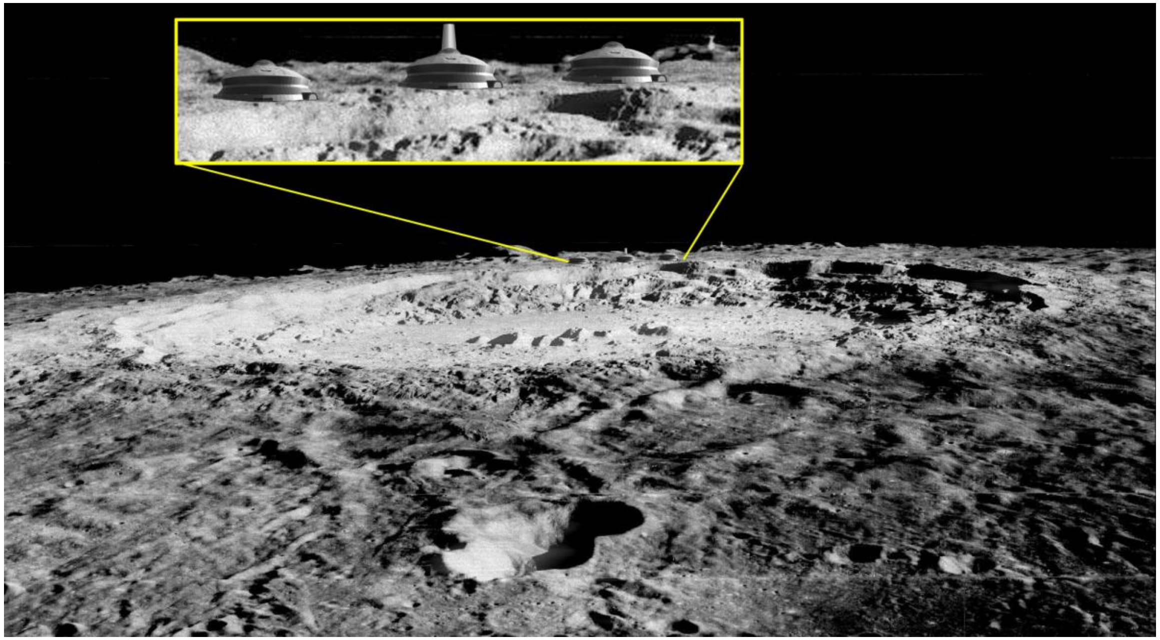
  Analogy to "Hello Kitty"— Products using Hello Kitty in their designs and logos are marketed by other firms that pay the Sanrio Corporation, the owner of the Hello Kitty brand, a licensing fee of 3% to 10%.

- **Rocket Mortgage**
- **Lunar Pizza**
- **An Out of This World Experience**
- **A Heavenly Night's Sleep**

- **Total estimated co-branding value: $84B to $560B (Details in separate report)**

More Stuff To Do on the Moon: The Grand Copernican Rim Hotel and DownHill Ride





- The crater Copernicus—visible from Earth at the edge of Oceanus Procellarum
- The "Grand Copernican Rim Hotel" is 3.5 km above the crater floor and 93 km from the opposite rim—seen as sharp and crisp as if it's right in front of you
- From the top of the rim to the crater floor the wall slopes downward, dropping 3.5 km (12,000 ft) over a distance of 19 km in a series of rolling terraces
- In 1/6th g, it's the downhill ride of a lifetime, taking about an hour at an average speed of 35 mph, with lots of twists and turns—a roller coaster ride like nothing on Earth

What Should We Put in the Mountains in the Middle of Copernicus?

- What do you think should be there?
- For me, I like the idea of the Copernicus World Library—a collection of all of the knowledge of the world (nearly all in digital form) in a location that will last for hundreds of millions of years
  - The Copernicus crater was formed about 800 million years ago (the dinosaur extinction was about 65 million years ago) and is still very fresh—one of the youngest craters on the Moon
  - Data could be accessible to all the world via the internet
- Data transmitted between the Earth and the Moon via laser comm links
  - Data rates of up to 10 GB/sec (= 10,000 MB/sec)
  - 600 MB/sec to the Moon has already been done
- The environment is remarkably benign
  - Essentially no erosion; no hurricanes, volcanoes, storms, tsunamis—far more protected from damage and destruction than <u>any</u> location on the Earth

From an economic perspective, the question is, What are people willing to pay for in advance of need in order to begin the process of lunar colonization?

1. **Burial or Memorialization in the mountains in the center of the crater Tycho?**
2. **Knowledge stored in the Copernicus World Library?**
3. **Possibly both?**

Natural Resources – Mining ^3He

- ^3He is an excellent source of clean nuclear power with no radioactive byproduct and no potential for explosions
  - Use for power on the Earth (and during nighttime on the Moon)
  - Value = ~$3B/metric ton
- Exists at a low level in the solar wind and has accumulated over millions of years in the lunar regolith
  - Can be released by heating the regolith
  - Not available in useful quantities on the Earth
  - Has been substantial interest from Russia, China, and some individuals in mining ^3He on the Moon
  - ^3He can be a major source of clean energy for Earth and income for the Moon
- Other natural resources of value for Earth or elsewhere in the solar system
  - Silicon and building materials for solar power satellites
  - Water for rocket fuel for solar system exploration and Earth-lunar transportation
    - If not enough water, can use oxygen from the lunar regolith

The Moon has significant physical resources that have high value on the Earth and for exploration of the solar system.

Economic Justification Revisited

- **For countries**
  - **No country or culture wants to be left behind when mankind starts to advance into the solar system in a way that is literally visible to the whole world**
- **For companies and entrepreneurs**
  - **More ways to make money and create "external revenue" than any city on Earth**
    - **Service and entertainment—tourism, movie production, TV specials**
    - **Essentially unlimited energy and natural resources**
    - **Science, high tech, and environmental monitoring**
    - **Transportation and exploration, on and off the Moon (lunar diamonds?)**
    - **Manufacturing, building—for the Moon and in space**
    - **And using everything that's there for advertising and co-branding**
- **For individuals**
  - **More jobs for skilled labor than anywhere on Earth**
    - **Monitoring and repair of everything from huge space telescopes to bicycles and toasters—nothing gets thrown out**
    - **Tourists from every country on Earth on very expensive vacations need someone to speak their language and show them around**
  - **The chance to be a part of the future, explore where no human has ever been, and discover places and stuff that no one has ever dreamed of (example: lunar caves on the far side of the Moon)**

Bottom line—there is a greater economic justification for settling the Moon than there has been for <u>any</u> location on Earth. It will likely create a great many lunar billionaires.

Revised Cost Model

- **Non-Recurring Cost to Set Up the Lunar Colony**

Category	Per Office or Service Worker	Per Explorer	1,000 People
Development and Acquisition	0.5t = $0.5M	2.5t = $2.5M	1,200t = $1.2B
Additional "Colony" Equipment	—	—	800t = $0.8B
Transportation Cost (low-cost)	$0.8M	$4.0M	$3.2B
Nitrogen Tax (250,000 × $40,000)	—	—	$10B

Our revised Cost Model Is Pretty Reasonable with income far in excess of cost.

- **Recurring Cost**

Category	Per Office or Service Worker	Per Explorer	1,000 People
Transportation Cost (resupply & crew exchange every 3 years)	0.2t = $0.3M/yr	1.0t = $1.5M/yr	500t = $0.8B/yr
Personnel Cost—On the Moon	$0.15M/yr	$1.2M/yr	$150M/yr
Misc. equipment/Nitrogen resupply	—	—	600t = $1B/yr

Still using a factor of 50 reduction in transportation cost, our 1,000-person lunar colony now costs $3 billion to create, $13 billion to get to the Moon over several years, and $2 billion/yr to support, with no more than 10% from one company or country.

And, of course, generating over $100 Billion/yr in income.

Does It Make Sense?

- **Why does it cost a factor of 10 less than the Space Station?**
  - — We have assumed a factor of 50 reduction in launch cost (that's critical)
  - — 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"
    - What was the cost of designing and building a chair for the ISS?
    - The first lunar chair is a rock brought in from outside and dusted off
- **Is it real?**
  - — Requires a factor of ~3 reduction in inherent launch cost—not that hard
    - Requires 2,000 launches to put it in place plus an additional 300 launches/year for resupply so the added factor of 3 due to economies of scale seems reasonable
  - — We haven't yet done serious engineering —simply a top level assessment
  - — Inconsistent with every aerospace cost model ever created—but cost models are built on how things used to be done, not how they can be done or will be done

The main thing required to make it happen is REINVENTING SPACE—a transformation in how we think about the Moon and space colonization.

Steps to Getting There

We'll talk about this in more detail later.

Step 1. Create a detailed economic and physical model

- The goal is not to follow it, but to show what is possible
- "Advertise" like H---
- May make some money along the way

Step 2. Make at least some significant reduction in launch costs

- Lots of alternative approaches are possible
- This begins to generate real income

Step 3. "Real estate developer" begins making real estate on the Moon

- Build a small lunar colony which serves as the base for building a larger one and as a "safe haven" for the first large colony
- Begin to need regulations at this point to avoid price gouging

Step 4. Create a Lunar Government

- Need zoning ordinances, regulation of utilities and prices, and safety regulations

Step 5. "Lunar Air, Water, and Electric Corp." (LAWE) begins building the utilities infrastructure

Step 6. Begin development of the colonies themselves

- Land within each colony is sold or leased, just as any other real estate development with a reasonable split among agriculture, hotels, businesses, and living facilities
- Properties within the colony are bought and built by governments, companies, and individuals within the limits of the local zoning restrictions
- Businesses develop to satisfy unmet needs, within regulations

Creating a Space Transformation – Getting Started

- **The goal is to create a literal transformation in space—in how we think about it, and, more important, how we do it**

Step 1A—Convince ourselves, the technical community, and the economic community that it absolutely is real by doing several things

- — **Economic analysis of the lunar colony**
- — **Create a Transition Plan laying out how to get there, how much it costs each step of the way, and the potential for ROI**
  - — **The issue is not to describe how it will be done (there are lots of ways), only to show that it can be done and here is one way of doing it**
  - — **Implies we're looking for a grant or other way to fund a study**

Step 1B—Begin changing the world

- — **Speeches, radio shows, books, TV series, and discussions of ROI to every investor group that we can talk to—It takes hard work to change the world**

Colonizing the Moon is no different than settling California or Alaska, only a bit easier because there is constant communications and resupply. It's not a "techie" activity. It's a people and business activity—with a mix of entrepreneurs, service workers, engineers, scientists, explorers, and very busy Maytag repairmen

One thing is certain—If we don't try, we won't get there.

Back-Up Data

— Other Methods of Reducing Cost

— Basic Properties of the Moon

— Lunar Materials Used to Build Colonies

More Economic Strategies to Reduce Cost: Spreading the Cost Among Multiple Groups

- What did it cost to settle and run California?
  - — No one knows, and, in the end, no one cares
  - — Thousands of people, companies, and governments each with their own motives
  - — Some made money, others did not
- Similarly, we should not regard lunar colonization as a single project to be funded by "somebody," but as an independent series of related activities
- Governments
  - — Diplomatic outposts, exploration, colonization, science, prestige
- Corporations
  - — Profit making from virtually any of the activities
    - — Example: Building the colonies creates real estate which is then sold, leased, or rented, just like land on Manhattan
  - — Advertising and prestige ("Universal Pizza")
- Individuals
  - — Tourism
  - — Investment, exploration, and entrepreneurship

Profit and prestige are among the driving motives; therefore we may need rules to limit investment, such that no one country or organization gains a monopoly.

Reducing Ground Operations Cost

- Relatively easy to reduce cost — eliminate it completely
- Colony governs itself (the "lunarites" probably wouldn't allow any alternative)
  - Makes and enforces rules and regulations, many of which will concern health and safety in a small, closed life-support system
  - Will almost certainly levy taxes for public works
- Independent transportation systems operate under their own regulations, those of their government, and any imposed by the lunar government (just like airlines do)
- Diplomats and government employees operate under control of their own government, just as they do in foreign countries
- Corporate employees operate under their corporate and management rules
- Individuals are free to do as they like in their free time, most don't have a lot of free time to do it in—stuff is expensive on the Moon and you will have to work hard to live there

There are plenty of part-time bureaucrats on the Moon, so, unfortunately, we can expect all of the inefficiencies of any other small metropolis.

Basic Properties of the Moon Relevant to Lunar Colonies

• Properties of the Moon and Earth

Property	Earth	Moon	Moon/Earth Ratio
Mass	6.0×10^{24} kg	7.4×10^{22} kg	1.2%
Equatorial Radius	6,378 km	1,738 km	27.3%
Surface Area	5.1×10^{8} km^2	3.8×10^{7} km^2 *	7.4%
Mean Density	5.5 g/cm^3	3.3 g/cm^3	60.5%
Gravity at the Equator	9.8 m/s^2	1.6 m/s^2	16.5%
Orbital Velocity	7.9 km/s	1.7 km/s **	21.3%
Escape Velocity	11.2 km/s	2.4 km/s	21.3%

* Equals the combined area of North and South America

** Equals 3,800 mph = Mach 5 at Earth sea level

• Orbit Properties of the Moon

Mean Distance from Earth	384,000 km
Synodic Period (= time from local noon to local noon)	29.5 days
Orbit Transfer Time (Hohmann Transfer)	5.0 days
Brightness of the Full Earth	80 × the Full Moon

- **Mean surface temperature of the Moon ranges from 107ºC (= 225ºF) during the day to –153ºC (= – 243ºF) at night; however temperature means very little without an atmosphere**

Material Known to be Present on the Lunar Surface

- The regolith (lunar soil) is typically 5 m to 15 m thick and consists of a fine grain, compact dust. It supports weight very well, but is easily charged with static electricity and is a major contaminant of equipment

- Average composition of the lunar regolith by weight:

— Oxygen	45%	— Silicon	21%
— Aluminum	5% to 13%	— Calcium	9%
— Iron	6% to 15%	— Magnesium	5%
— Titanium	1% to 5%		

- 1% to 25% of the lunar regolith is made up of lunar glass formed largely from impacts

- Biogenic gases (carbon, nitrogen, and hydrogen) are present in the regolith with concentrations of approximately 0.01% by weight. These can be released by heating the soil to 700ºC

- The regolith is also rich in ^3He from long term exposure to the solar wind which could be an excellent source of nuclear power for the Moon and the Earth

- Recent Lunar Prospector mission found very strong evidence for large quantities of H_2O located in polar craters for which the bottoms never see sunlight

Materials on the Lunar Surface Appropriate for Use in the Lunar Settlement

- Oxygen is readily available in large quantities
- Aluminum for structural material and silicate for glass are available in large quantities and should be the basic building materials for a colony
- Water appears to be available in the polar regions
- Both silicon for solar cells and ^{3}He for nuclear power are also available
- The principal raw materials that are available only in small quantities are nitrogen and carbon
- The regolith itself (after removing whatever minerals are wanted) is excellent for both radiation shielding and thermal insulation

The basic bulk raw materials are readily available on the Moon.
The biggest problem is Nitrogen for the atmosphere.

Epilogue

- "Hubris took America to the Moon, a barren soulless place where humans do not belong and cannot flourish. If the voyage has had any positive benefit at all, it has reminded us that everything that is good resides on Earth."

Gerard J. Degroot, 2006
"Dark Side of the Moon, The Magnificent Madness of the American Lunar Quest"

- Degroot's arguments are well-researched, well-written, well-expressed, and total bull
- Why would anyone choose to live on the Moon?
  - Partly for the adventure
  - Partly to protect and expand civilization
  - Partly to protect the Earth, and
  - Partly to make money, lots of money
- As most people know if they think about it a bit, the title of Degroot's book is fundamentally a misconception — there is a near side of the Moon, and a far side, but there is no dark side. It does not exist.
- The goal of this presentation is to show that while Degroot's arguments may be believed by many people, they have about the same level of validity as those of the "Flat Earth Society" of the 15th century

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