Space 2018

Reinventing Space

Making $100 Billion/year Living and Working on the Moon

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TOPICS

- Background – The Problem of How to Create Truly Low Cost Lunar Colonies
  - A Traditional Cost Model
- Reducing Cost 1 -- Reducing Transportation Cost and Its Impact on Lunar Economics
- Reducing Cost 2 -- Working Indoors and Using Ordinary Equipment
  - What Should a Lunar Colony Look Like?
- Reducing Cost 3 – The Income Side: What Activities Will Generate Return on Investment
  - What is There to Do on the Moon that Brings in $100B?
  - Answer = Lots of Stuff
- The Revised Cost Model
  - Does It Really Make Sense?
  - How Do We Get There?
- Back-Up Data
  - Resources Available (and Not Available) on the Moon
  - Safety Issues
  - Other Issues
  - Epilogue – the Dark Side of the Moon

THE BOTTOM LINE

- It's been nearly 50 years since Apollo, and human settlement of the Moon is still a ways off
- If we're going to create near-term lunar colonies, <u>something</u> has to change dramatically
- That "something" is the basic motivation for doing it. Specifically,

I believe that you can make $100 billion/year (and likely much more) in the near term living and working on the Moon.

- 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

PARTIAL LIST OF SOURCES OF EXTERNAL INCOME FOR AN ACTIVE AND GROWING LUNAR COLONY

Source	Basis (per year)	Annual Income
Tourism	600 tourists/mon = 7,000/year@ $1M–$2M each	$7B–$14B
Space Burial	100,000 to 500,000@$5K–$20K each	$0.5B–$10B
Helium-3	10–30 tons @ $3B/ton	$30B–$90B
Diplomats/National Representatives	200 people $1.0M/person	$0.2B
Entertainment and the Arts	???	$2B–$10B
Mining/Minerals (except ^{3}He)	???	$2B–$10B
Science	Astronomy, Geology, Biology, Physics, Chemistry	$2B–$5B
Solar System Exploration	20% of NASA budget + commercial	$5B
Solar Power Satellites	2–10 @$8.5B each	$17B–$85B
Knowledge Preservation (Lunar Library)	???	$0.5B–$1B
Manufacturing	Low and 0-g manufacturing, structural components for use in space	$2B–$5B
Co-Branding	(Separate estimate available)	$85B–$560B
Total Annual External Income		**$152B–$795B**

Individual income sources will be discussed later.

Substantial additional economic analysis needs to be done on income estimates.

PRACTICAL REINVENTING SPACE: THE CRICITCAL ISSUES FOR SPACE COLONIZATION

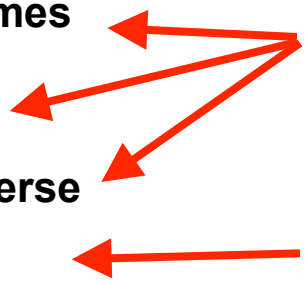
- Most discussions of space colonization focus on technology issues such as where we could live or how we would get there
- But the most critical issues are more straightforward – motivation and money

If people are going to live and work on the Moon, Mars, or anywhere else in the solar system, who is going to pay for it, and why? It won't be cheap, so what will these people do for a living other than eat, sleep, and pick up rocks?

Answer:

Whatever it is that either generates income or that others will pay for.

- Why would we colonize the Moon or Planets?
  1. To preserve humankind if the Earth becomes uninhabitable
  2. To explore and experience new lands
  3. To expand human presence into the Universe
  4. To make money – lots and lots of money
- Who is going to pay for it?
  - Possibly all of us collectively, Possibly whoever wants a new way to make lots and lots of $$$

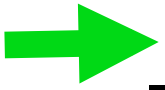


These are real, but aren't seen as critical or immediate for most of the people around us.

A less lofty goal, but understood by most people.

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, but that's a discussion that takes far more time than we have here
- 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 colony, we're going to have to <u>BOTH</u> dramatically reduce cost with respect to traditional programs and find ways to use the colony to generate very large amounts of $$$.

REDUCING COST METHOD 1 -- REDUCING 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
  - **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

USING A TRADITIONAL APPROACH, EVEN WITH 50 TIMES LOWER TRANSPORTATION COST IS FAR TOO EXPENSIVE

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

	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 DRIVES THE COST OF THE COLONY.

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

	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 x 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 colony 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 hurricanes and natural disasters.

ECONOMIC OBJECTIVES FOR A REALISTIC, NEAR-TERM, LOW-COST LUNAR COLONY

- 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.

REDUCING COST METHOD 2 – WORK PRIMARILY INDOORS

- **Most important for real cost reduction: work primarily inside, rather than outside**
  - 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 no 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; Consider using mining or underwater equipment

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

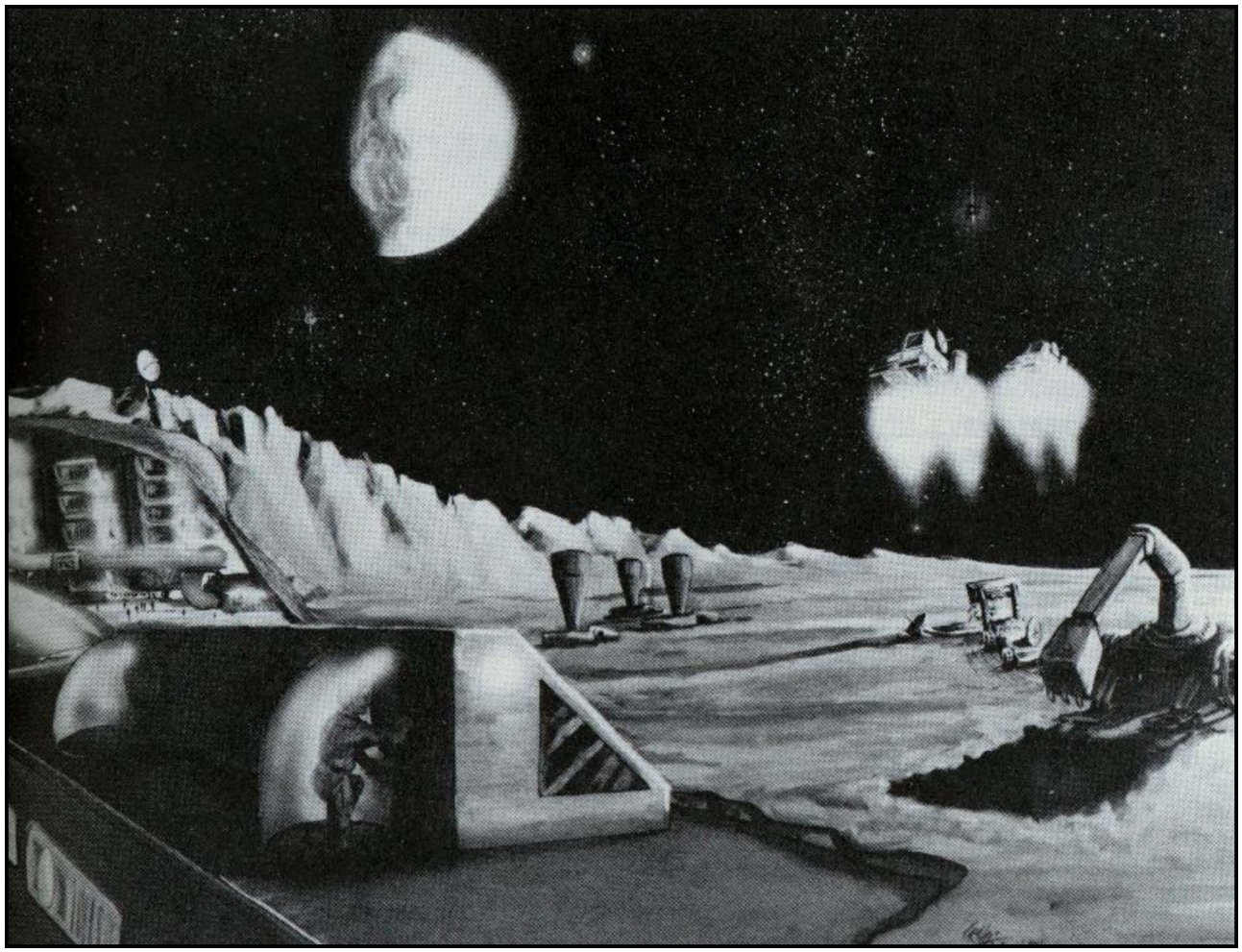
RELATED COST-REDUCTION TECHNIQUES

- **Use existing lunar resources in a cost-effective fashion, not for anything complex**
  - **Use lunar material for massive, simple structures and objects**
    - **The colonies themselves—structure (aluminum & glass) and radiation shielding (regolith)**
    - **Walls, desks, tables, chairs, bookcases**
  - **Use lunar H_2O and O_2—sadly, lunar colony 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.

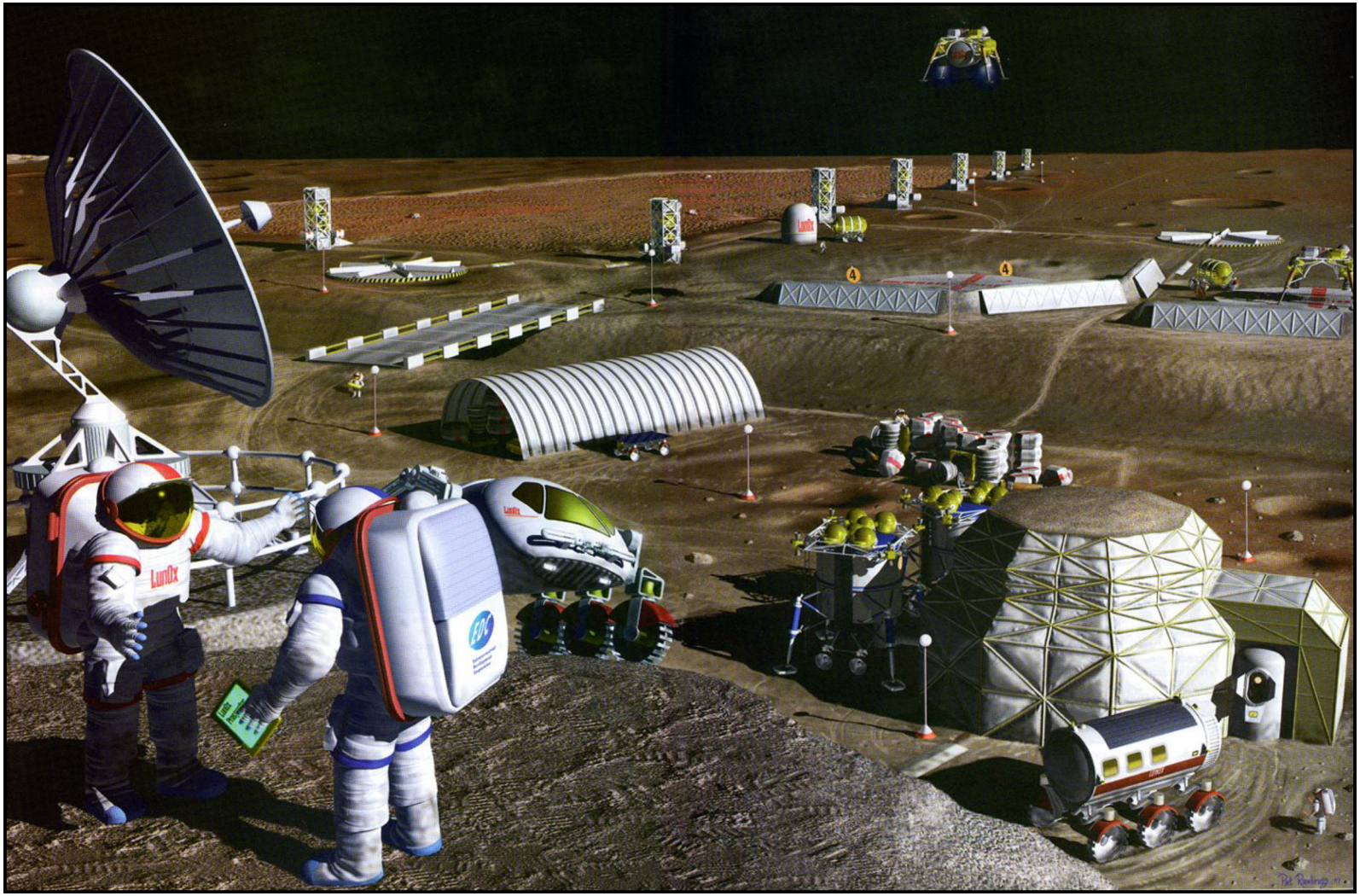
THE TRADITIONAL LUNAR COLONY IS FUNDAMENTALLY HOSTILE TO PEOPLE

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



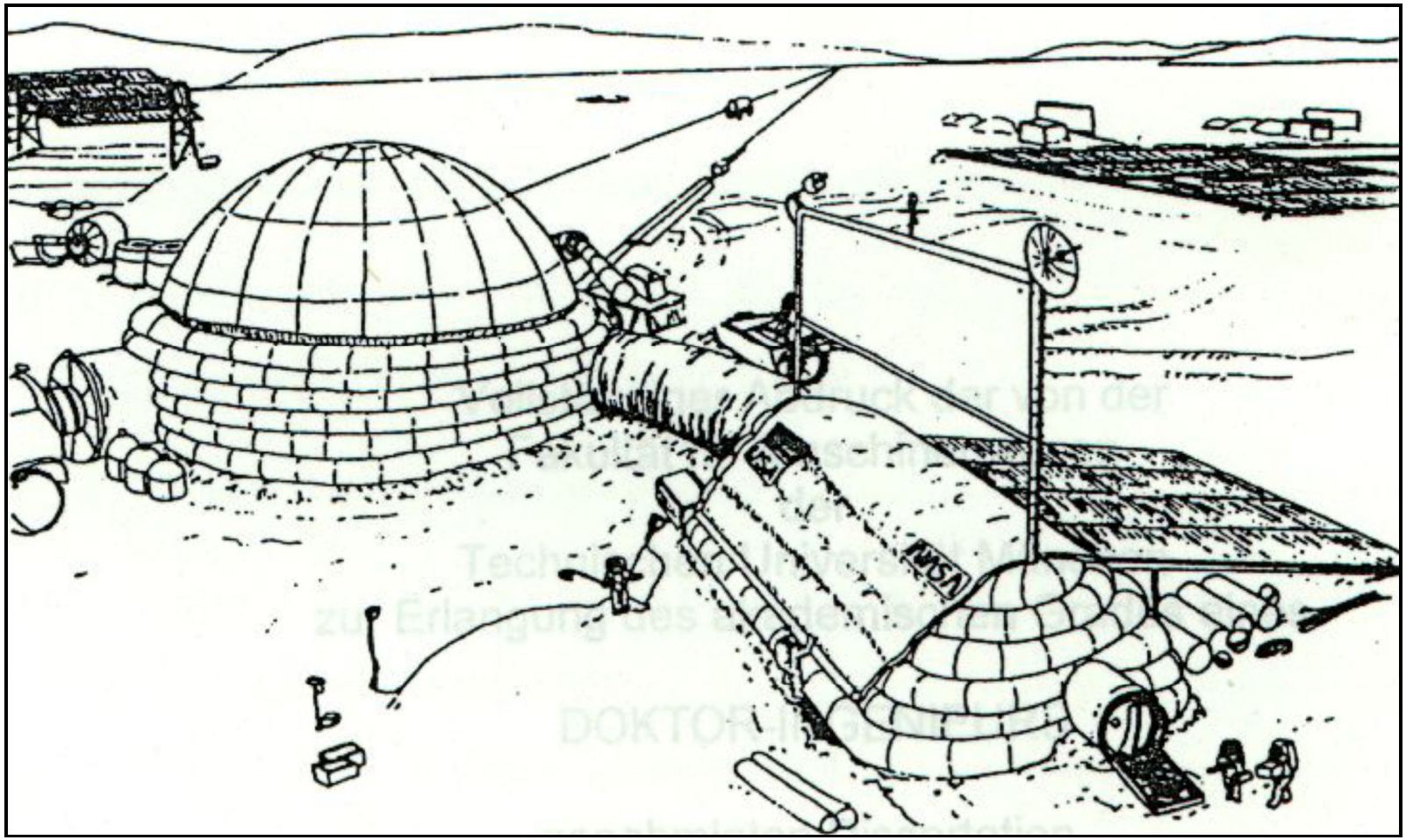
IN THE TRADITIONAL LUNAR COLONY MOST WORK IS DONE OUTSIDE

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

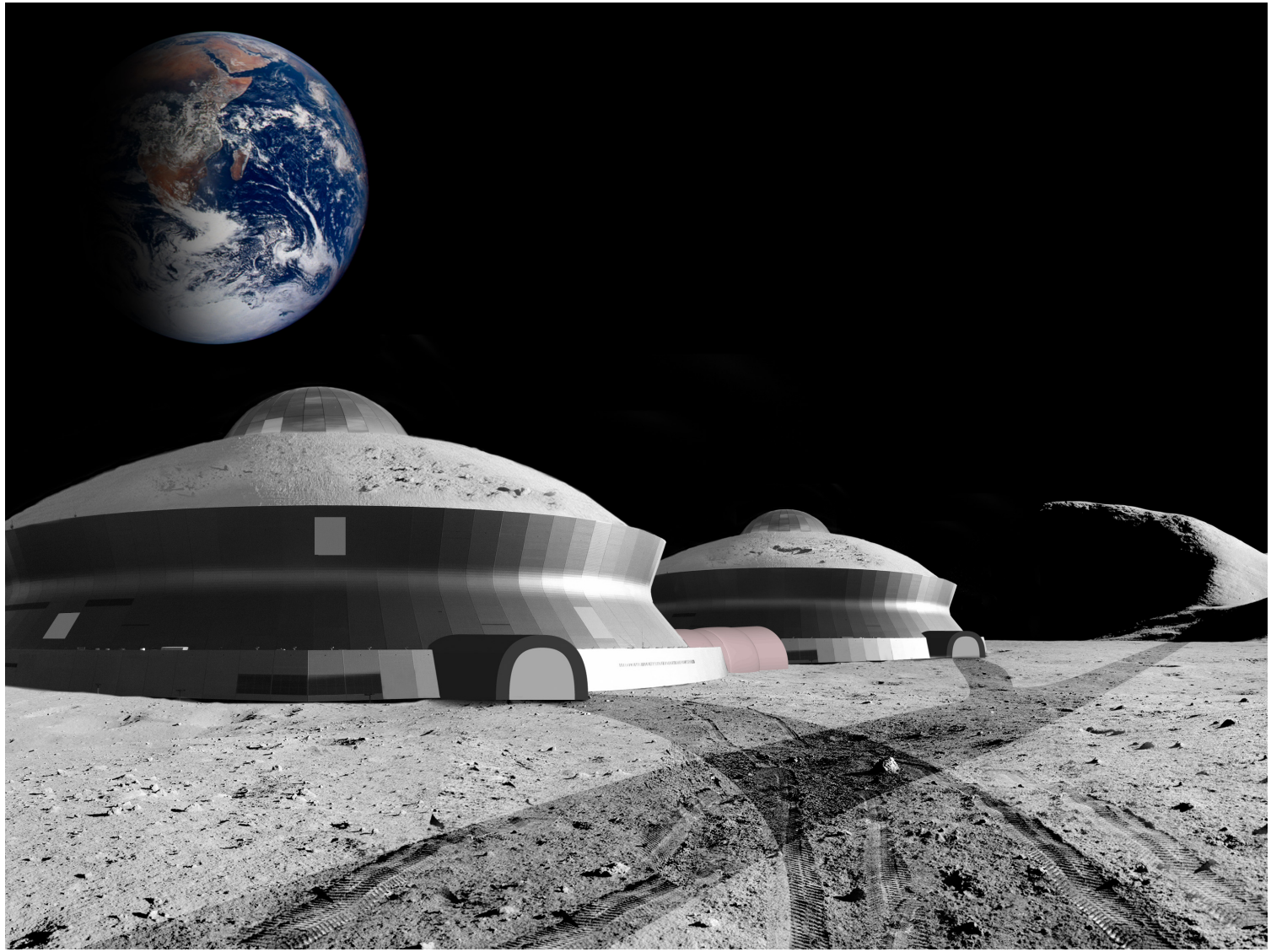
- In Eckart's model, the conditions are sufficiently harsh that stays are limited to 3 months (crew rotation 4 times per year)



WHAT SHOULD A LUNAR COLONY 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 (approximate 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

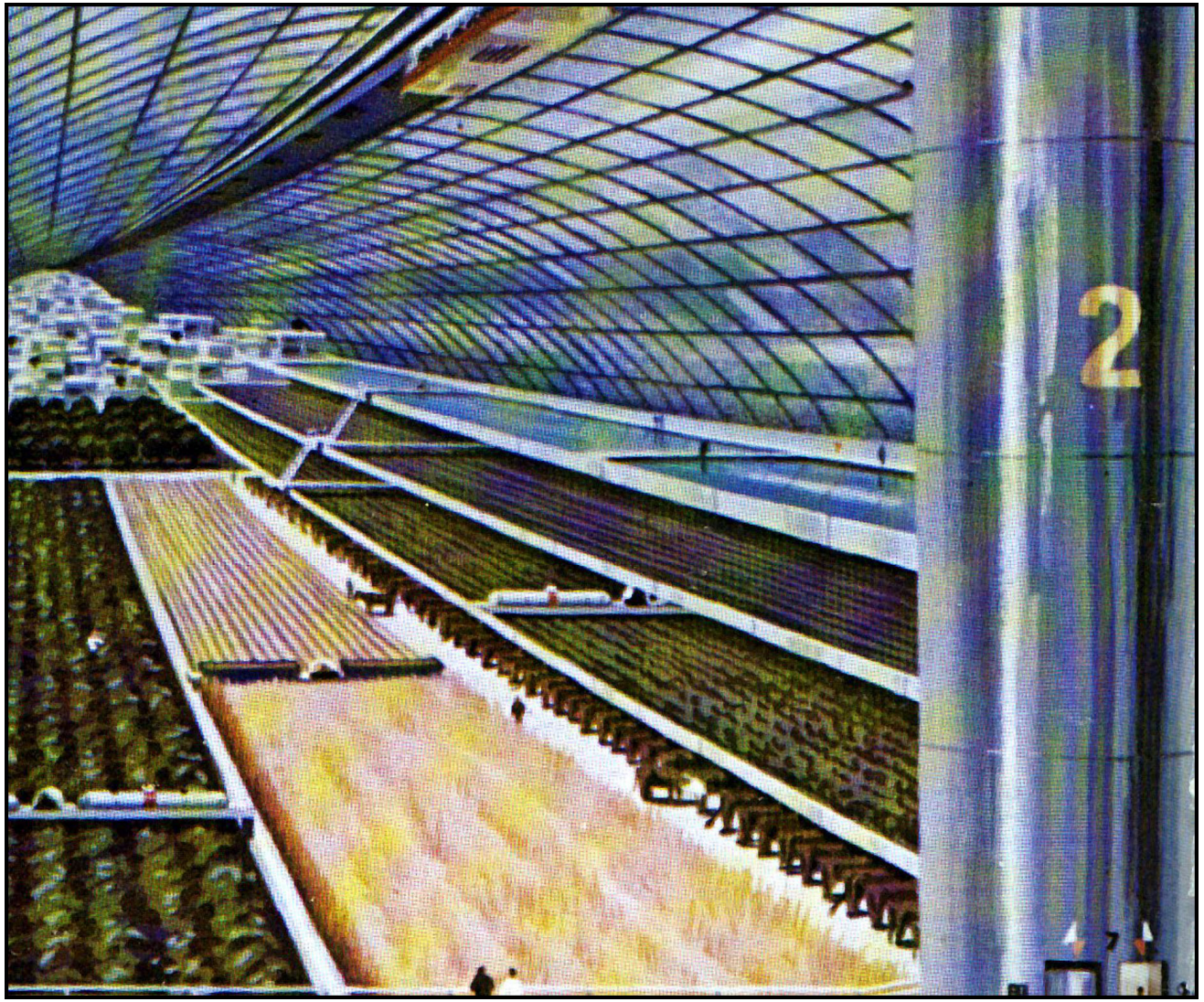
REPRESENTATIVE LUNAR COLONY – EACH DOME HAS TWICE THE AREA OF A 100,000 PERSON SPORTS STADIUM



INTERIOR OF A MORE PEOPLE-FRIENDLY LUNAR COLONY 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



REDUCING COST METHOD 3 -- INCOME : WHAT ACTIVITIES ON THE MOON WILL GENERATE RETURN ON INVESTMENT?

NOTE: Because of the high labor rates, many people will hold multiple jobs

- **Tourism — hotels, tours, events, marketing (key enabler for other income sources)**
- **Entertainment and Arts — professional sports, specials, educational TV (multi-lingual and multi-cultural), photography, art (static and performances), advertising and marketing (makes the Moon a part of everyday culture)**
- **Mining — materials for lunar consumption, gemstones, minerals, water for rocket fuel**
  - **^{3}He — a major source of clean nuclear energy available in the lunar regolith (major income generation)**
- **Sciences — astronomy, geology, biology, physics, chemistry**
- **4 Diplomats/Representatives from 50 countries with >15 million people (population of the Netherlands or Texas) = 200 people**
- **Engineering and Technology — materials, low-gravity construction, spacecraft built from lunar materials, launch and propulsion technologies; ultra-high and ultra-low temperature environments**
- **Exploration — scientific and commercial**
- **Transportation — on the Moon, Earth-Moon, asteroids and comets, elsewhere in the solar system; people and freight (central hub for solar system exploration)**
- **Education — Real-time discussion of life on the Moon—broadcast in every language to every culture around the world**
- **Space Burial in Crater Tycho — Can be seen from anywhere on Earth at Full Moon**

Red = generates outside income
Green = predominantly internal spending

MORE INCOME GENERATION ON THE MOON

- **Solar Power Satellites — build on the Moon for transport to GEO or LEO (major income)**
- **Manufacturing for export — structural components for space stations, satellites, and space vehicles; low-g and 0-g (in low lunar orbit) manufacturing, pharmaceuticals, semiconductors; vacuum and low pressure manufacturing**
- **Co-Branding — Moon cars, rocket mortgage, lunar pizza, out-of-this-world bargains (may be the largest source of outside income)**
- **Manufacturing for internal consumption — construction materials (metals, concrete, glass), building supplies (simple stuff—windows, walls, furniture, household products)**
- **Construction — building and maintaining new facilities for the Moon and space, roads, power lines, air lines**
- **Utilities — power, water, air**
- **Infrastructure — police, fire, medical, rescue, government and administrative**
- **Food — farming, markets, restaurants**
- **Environmental science and engineering — preservation of the lunar environment, monitoring and maintenance of the life-support environment, monitoring the solar-terrestrial environment**
- **New and used sales, rentals, and trades — if somebody brings it, sell it on the Moon**
- **Maintenance and repair — applicable to nearly all products—everything on the Moon gets repaired, reused, or recycled**

There are more potential sources of "outside income" on the Moon than for any metropolitan or commercial area on Earth.

SOURCES OF EXTERNAL INCOME FOR AN ACTIVE AND GROWING LUNAR COLONY

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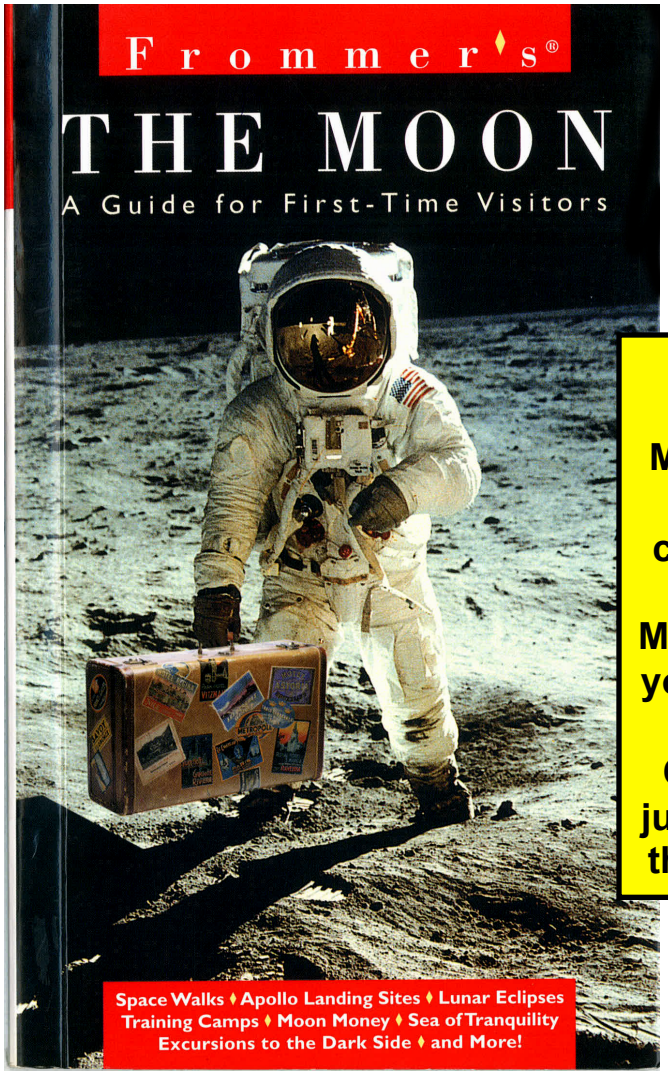
Total Annual External Income		**$152B–$795B**

Substantial additional economic analysis needs to be done on income estimates.

THERE IS A VERY REAL INTEREST IN A LUNAR COLONY LARGE ENOUGH TO SUPPORT TOURISM

- ***Frommer's "The Moon, A Guide for First Time Visitors"*** **is indicative of the interest.**
- **The science and engineering community tend to regard "people activities," such as tourism, advertising, or space burial as irrelevant, inappropriate, or as a distraction to science and exploration, whereas they may be among the largest sources of income on the Moon and the principal driver of interest and support.**

The economic engine for the Moon is driven by "people activities" and physical resources.



Even in downtown Manhattan, you could turn a corner, look up and see the Moon, and say to your companion "I was there. Our hotel was just to the left of the terminator."

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)**

PRELIMINARY ANALYSIS OF INCOME SOURCES

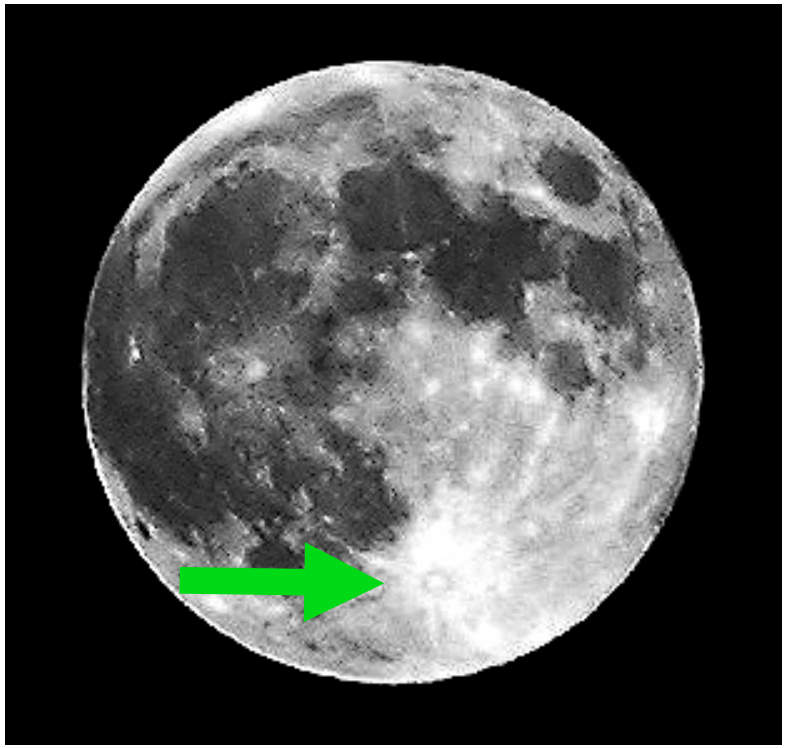
- Lunar tourism provides the high level of transportation and activity that enables other missions at low cost
  - ~7,000 tourist trips/year and growing when the colony reaches 1,000 residents (for comparison, annual visitors are 1,500,000 for Guam and 70,000 for American Samoa)
  - Tourism + lunar burial provide the basis for getting the colony started ($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 one of the two 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
  - Some of these could become very large

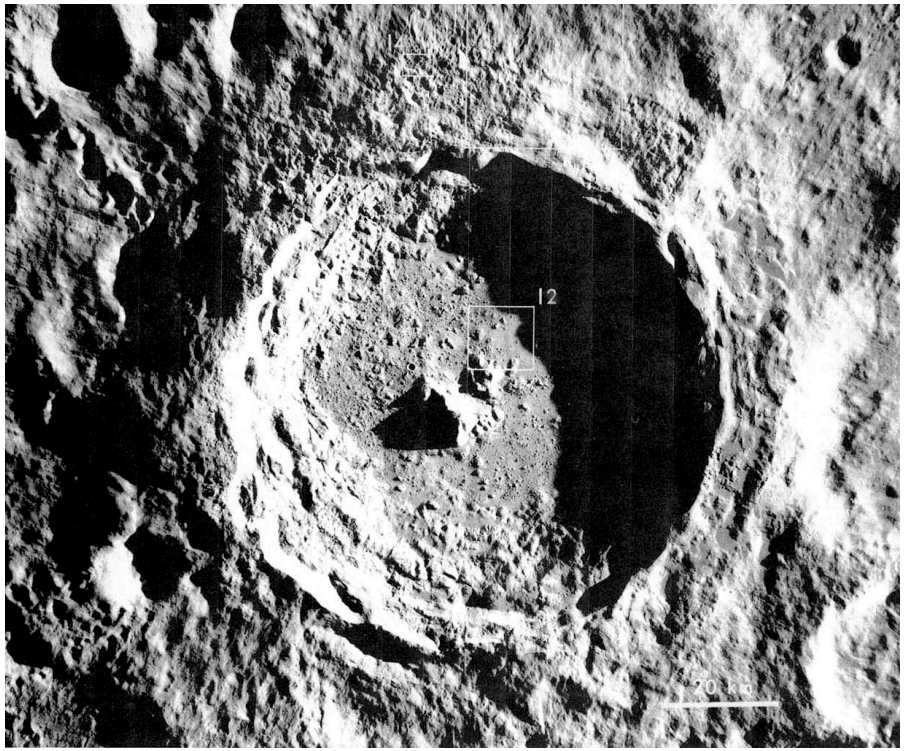
A key issue for the development of the lunar colony is a more detailed economic analysis of both costs and income from multiple sources.

WHAT WOULD A TOURIST DO ON THE MOON?

- **Sit, stand, walk—at 1/6th your weight on Earth—every moment you'll know you're on the Moon**
- **Literally watch the Earth turn as the terminator stays fixed and, over the course of 3 hours, New York, then Chicago, Denver, and Los Angeles cross the sunset line into darkness**
- **Tour the mountains, maria, rills, and giant craters, some over 100 km across**
- **Recreation—bicycling, diving, swimming, gymnastics, basketball (no golf)**
- **Performances—dancers, performers, and athletes who hang in the air forever (more-or-less)**
- **Use a small telescope to see places on Earth you've never seen and views of the planets, nebulae, and galaxies with a clarity you've never seen**
- **Visit the Far Side Observatory, where you can see a side of the Moon no one on Earth has ever seen and, at night, look at a sky that is blacker than any on Earth—like going to the far side of Catalina island and looking at the vast expanse of ocean in front of you, only on a scale that is dramatically more vast**
- **Try on a space suit and walk on the surface of the Moon in the vacuum of space**
- **Try food from around the world cooked by people from around the world and try lunar veggie burgers (perhaps not a gourmet treat)**
- **And, of course, spend time in bed with you and your partner both weighing 1/6th of what you do on Earth**

VISITING THE TYCHO MEMORIAL PARK—THIS MAY BE A MAJOR PART OF THE LUNAR ECONOMIC START-UP





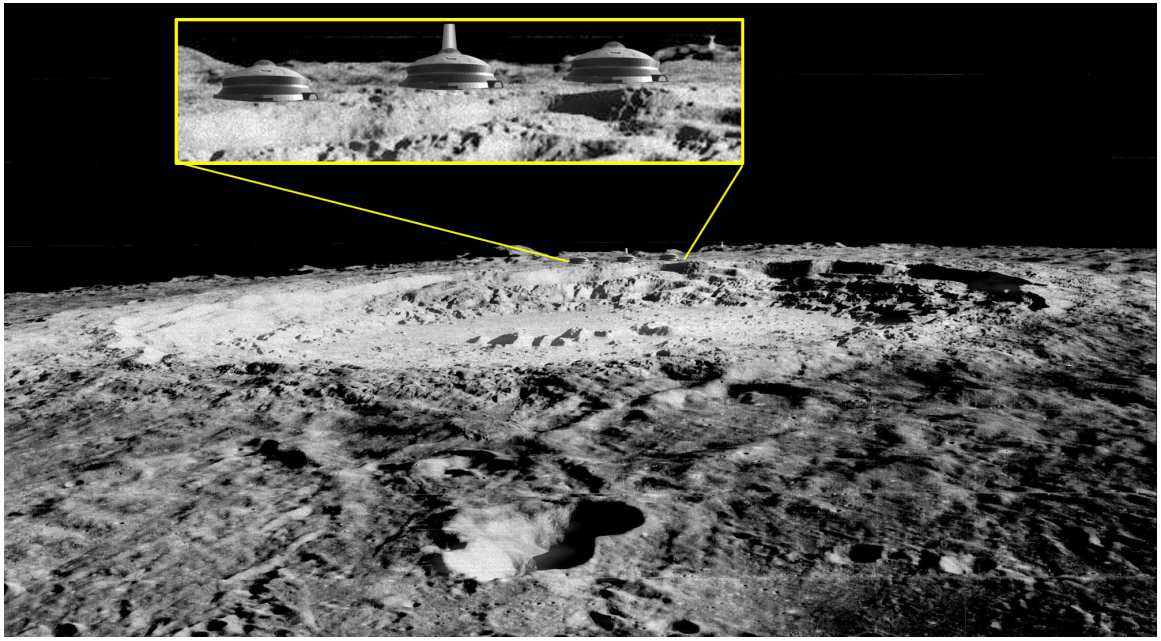
- The crater Tycho is hardly visible from Earth most of the month, but at Full Moon becomes the single most identifiable location in the Universe (Tycho is the crater in the bottom center of the photo on the left), visible from everywhere on Earth (over a 24-hour period) where there is a clear sky
- The Tycho Memorial Park, in the mountains at the center of the crater, will have small vials of ashes from people from throughout the world, perhaps some of your relatives, at a place in the heavens that can be seen by everyone on Earth, wherever they may be

LET'S STOP FOR A SHORT MOMENT AND THINK ABOUT THE PAST INSTEAD OF THE FUTURE

- For the moment, forget about astronautics and spaceflight and the future and think about the past—are there people that you want to remember who have died?
  - The victims of the Holocaust
  - President Kennedy or Martin Luther King or others who are heroes for you personally
  - The people beheaded by ISIS or those who were forced to flee their homes, many of whom were slaughtered
  - People that have been killed recently in airline accidents or terrorist attacks
  - Your own relatives who have died, your parents or grandparents, or a sibling, or friend
- At the next Full Moon take 1 minute and go outside and look at the Moon and think about those that you want most to remember
  - Look for the crater Tycho—the most visible and identifiable location in all the heavens—and think about people who meant a lot to all of us or to you personally
  - What if there were a memorial to them, a small amount of ashes or a sample of DNA, right there in the middle of the Crater Tycho, that would stay there, not just for hundreds of years, but for hundreds of millions of years

Tycho is a unique location for those of us that still live on Earth, and there is the possibility that YOU could stand on the rim of Tycho and see the Earth overhead and mountains in the middle with a memorial for all of those who have gone before and made possible mankind's expansion into the solar system.

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 this is the downhill ride of a lifetime, taking perhaps 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?**

NATURAL RESOURCES -- MINING ^{3}He

- ^{3}He 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 ^{3}He on the Moon
  - ^{3}He can be a major source of clean energy for Earth and income for the lunar colony
- 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 for 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 generate "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 (example: 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 generate 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

- **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 is the cost of designing and building a chair for the Space Station?
    - 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 have not yet done serious engineering — have simply done 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

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 alternatives), 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, movies, 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

- Resources available (and not available) on the Moon
  - The Nitrogen problem
- Safety issues
- Other issues

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%
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**

Property	Value
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) to –153ºC (= –243ºF); however temperature means very little without an atmosphere; 30 cm into the lunar soil the temperature is essentially constant**

In some respects the lunar environment is very harsh and unforgiving. On the other hand, floods, tornadoes, hurricanes, and tsunamis don't exist. (There are small Moonquakes.) There are no poisonous snakes, plants, lizards, or insects, no indigenous folks who would strongly prefer that you go back where you came from, and nothing in the environment regards you as lunch—and that's pretty good.

BUILDING SUPPLIES 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%
  - Aluminum 5% to 13%
  - Iron 6% to 15%
  - Titanium 1% to 5%
  - Silicon 21%
  - Calcium 9%
  - Magnesium 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

- There is strong evidence for large quantities of H_2O located in polar craters for which the bottoms are never in sunlight—but we don't know how easy it is to get at

MATERIALS ON THE LUNAR SURFACE APPROPRIATE FOR USE IN THE LUNAR COLONY

- Oxygen is readily available in large quantities
  - Also is the heaviest part (89%) of the propellants needed for a hydrogen/oxygen rocket engine
- 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.

THE NITROGEN PROBLEM

- 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:
  - Brought from the Earth's surface—major source to start
  - Recoverable by product from the air around goods and people brought to the Moon
  - Scooped by satellite from the Earth's upper atmosphere
  - 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 to 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)
- For working purposes we will assume a colony interior height of 35 m, composed of 3 psi O_2 and 10 psi N_2
  - Assume initially that all of the nitrogen comes from the Earth's surface
  - Gives cost of N_2 of $40,000/$m^2$ of the colony area

RISK MITIGATION AND SAFETY— VERY IMPORTANT ON THE MOON

- Radiation
  - Provide mass equivalent of Earth's atmosphere between the colony and space
  - 15 psi Earth equivalent shielding = 5 m of lunar soil over an aluminum structure
    - Soil on the roof weighs 2–3 pounds per square inch
    - Could probably do with less
    - More pressure from the inside atmosphere than weight from the soil
  - Principal protection for people who are outside is adequate warning to go inside in case of solar storms

- Asteroid Hit
  - Danger no different than on Earth—asteroid not significantly slowed by Earth's atmosphere and the consequences of a direct or nearby hit are similar

- Loss of Colony Atmosphere (leaks, meteoroids, someone forgot to shut the door)
  - Meteoroids stopped by the regolith used for shielding
  - In a large volume like the colony, air loss through even a large hole is slow, allowing time to find and fix the problem
    - Need warning system to immediately detect any loss in air pressure
    - May want rubberized liner (similar to automotive tires) or dual pane windows (similar to those used in cold climates)
    - Will want to be able to seal off some interior buildings and have O_2 available at many places to provide back-up in case of catastrophe

RISK MITIGATION AND SAFETY (CONT.)

- Loss of air supply on the surface (leaks, mechanical breakdowns, lost or injured)
  - While outside, maintain continuous communication with the colonies
  - Major roads should have a supply line with air, power, and communications
  - Carry back-up supply of air, power, and communications equipment
  - 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)
  - In today's world, continuous communications is critical and not hard—via cell towers, lunar satellites, or direct to Earth (as was done for Apollo)
- Fire and pollution—the biggest threats
  - Fires in any confined region are always a problem
  - For fire fighting, oxygen control is key—cut the fire off, supply it to people
  - Most substantial threat may be pollution—there is no ocean or atmosphere to dump stuff into (but that may not be the solution on Earth for too much longer)
    - Safety comes from careful monitoring and cleaning or replenishment as needed

The lunar environment is harsh, but benign. In many respects, building a colony on the Moon is much easier and less threatening than building a town on the Amazon.

BURIAL IN SPACE ISN'T NEW

- Informal burial in space has been around for many years, usually in the form of taking along ashes or some other memorial of someone who worked for many years to make a program happen
- The first commercial space burial started with Celestis, founded by Charlie Chafer in 1994
  - Suborbital flights
  - Orbital flights—two are currently in orbit
    - Includes Gene Roddenberry, the creator of Star Trek
  - Lunar flights—Eugene Shoemaker sent to the Moon in 1999; commercial flights may be scheduled soon
  - Celestis has had a total of 12 flights to date
- Typically what is launched is a 1 gm sample of cremated ashes as a memorialization to the person who has died
- After a traditional space burial the ashes are essentially "lost in space" (typically re-enter and burn up in the atmosphere some time after launch)
  - Has value for many, but, in my opinion, not the dramatic or broad-based appeal of being visible in the heavens at the Full Moon essentially forever

* C.M. Chafer, "Responsive Space Systems And Consumer Markets: The Celestis Case," Responsive Space Conf Paper No. RS1-2003-7005, April 1, 2003.

MORE ON ECONOMIC STRATEGIES FOR REDUCING 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.

USE OF LUNAR RESOURCES TO REDUCE COST

- Want to maximize the use of resources available on the Moon
  - All construction done with local materials
    - Metal and glass for structure (weight and strength are not a problem)
    - Soil (after valuable components removed) for insulation and shielding
  - Oxygen and water from the Moon
  - Silicon for solar cells for power generation

- Food production should be done on the Moon
  - Carbon and nitrogen can come from Earth, from asteroids, or from outgassing by heating the lunar soil

- Lunar manufacturing should be limited to simple, structural products where the mass of the products far exceeds the mass of the equipment needed to produce it

- Recycling is "In" on the Moon — either fix it, recycle it, use it for something else, or melt it down and start over

  - Additive manufacturing is in vogue today – on the Moon it is most likely to enable the local construction of spare parts which will help reduce the cost of maintenance and repair

Nearly all of the heavy items required for colonization can be mined or built on the Moon.

USE OF COTS PRODUCTS TO REDUCE COST IS A MAJOR COST SAVER

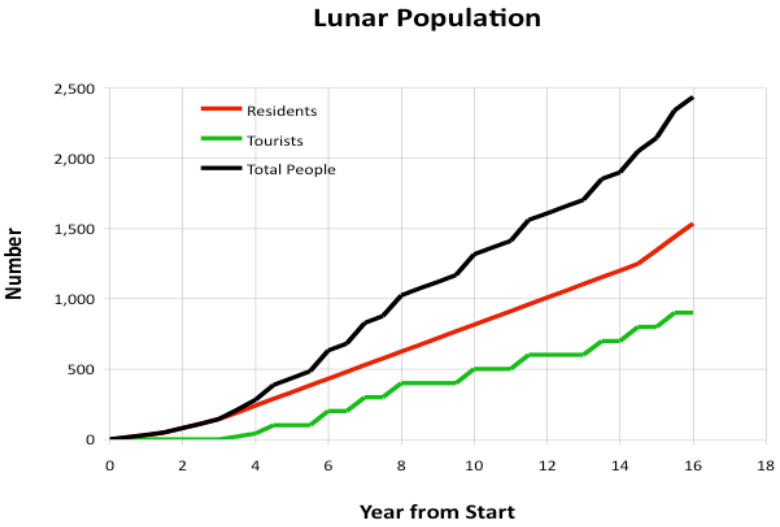
- Stuff brought from Earth is nearly all biological material or manufactured goods
  - Seeds, computers, voltmeters, iPhones, power tools, LCD TVs, bicycles, clothes, and spare parts
- Nearly all products used inside the colony can be COTS products direct from Earth
  - Most manufacturing and construction done inside using normal COTS tools
  - Most electric or mechanical products should work well as built
  - Transportation via bicycles, electric carts, or electric cars (no gasoline)
- Products for use outside can be COTS products modified for operation in vacuum environment with lots of dust
  - Transportation, lifting, and hauling equipment can be light-weight commercial electric vehicles or standard vehicles refitted for electric operation
  - Should explore use of underwater equipment for use on the lunar surface
  - Peopleware for outside is an interesting issue that should be explored
- Heavy rental business for tourist and visitors
  - Could rent cameras and clothes to tourists
  - Rent professional broadcast equipment to event sponsors
  - If someone brings new equipment, buy it from them for later use by others

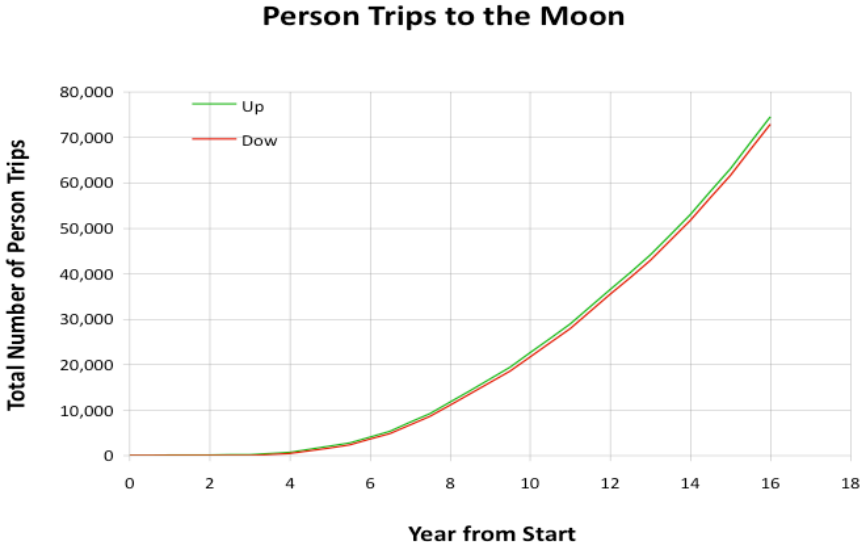
REDUCING GROUND OPERATIONS COST

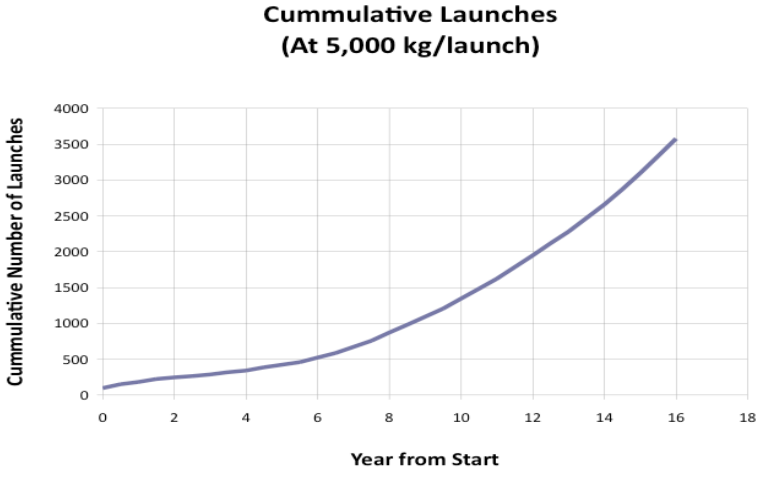
- Relatively easy to reduce cost — eliminate it completely
- Colony governs itself (the people involved probably wouldn't allow any alternative)
  - — Makes and enforces rules and regulations, many of which will concern health and safety in a small, closed life-support system
  - — Will almost certainly 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 own 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

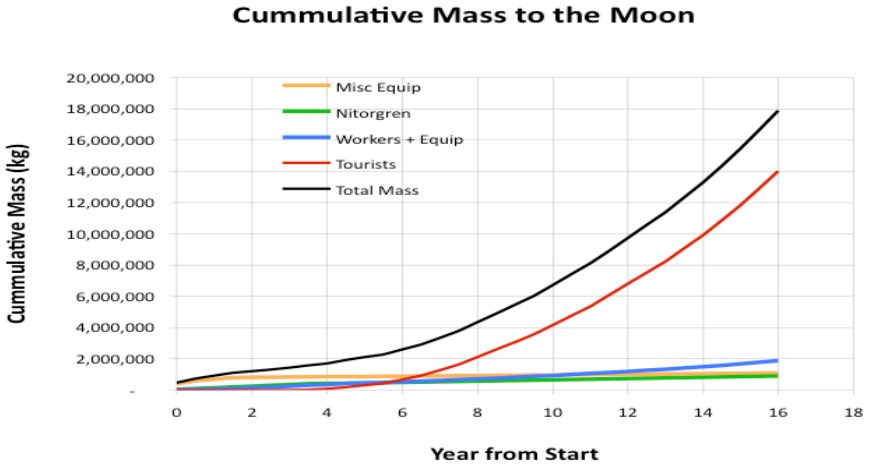
There are plenty of part-time bureaucrats on the Moon, so, unfortunately, we can expect all of the inefficiencies of any other small metropolis.

HOW DOES THE LUNAR COLONY GROW OVER TIME









The Lunar Colony reaches 1,000 people about 12 years after building begins.

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 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 <u>there is no dark side</u>. 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**