Space Resources

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Overview

- Basic Economics
  - What do we need?
  - Where will we get resources?
  - How will we get them?
- Products needed
  - Propellants
  - Water, oxygen
  - Free metals
  - Bulk shielding
  - Energy

Solar Power from Space (SPS)

- Utilize “unlimited” solar Energy
  - Solar Array at GEO
  - Not constrained by weather
  - Could provide 1g % of US E requirements
- Distinct Stages
  - Collect solar energy
  - Convert energy to microwave power
  - Transmit power to Earth
  - Collect microwave power
  - Convert microwave to electricity

SPS System Disadvantages

- Large up-front costs
- Crowding of GEO
- Transportation to GEO → HLLV
  - O₃ destruction
- Filling microwave window (2-4 GHz)
  - Kills further SETI research
- Environmental impacts
  - Heating within beam pattern
  - Rectenna arrays: lg. area (% of CA)
May be a clean, economic E source

Energy Comparisons

<table>
<thead>
<tr>
<th></th>
<th>Solar thermal</th>
<th>Solar photo</th>
<th>Wind</th>
<th>Ocean thermal</th>
<th>Solar SPS</th>
<th>Fusion</th>
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</thead>
<tbody>
<tr>
<td>Invest $ per kW</td>
<td>1300</td>
<td>1100</td>
<td>750</td>
<td>1200</td>
<td>4000</td>
<td>400 - 500</td>
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<tr>
<td>Capacity</td>
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<td>0.35</td>
<td>0.9</td>
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<td>Develop probe</td>
<td>Hello-stat</td>
<td>Material</td>
<td>Rotor</td>
<td>Heat exchange</td>
<td>Launch</td>
<td>Safety</td>
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<td>Dev $</td>
<td>$1B</td>
<td>$1B</td>
<td>$0.9B</td>
<td>$1B</td>
<td>$60B</td>
<td>$11B</td>
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<td>Time</td>
<td>2 yr</td>
<td>7 yr</td>
<td>1 yr</td>
<td>2 yr</td>
<td>15 yr</td>
<td>2 yr</td>
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</tbody>
</table>

Energy Consumption

- Average power Use (1 yr)
  - World uses 15 TW; US 21%
    - At 315 Million, US is 4.4% of world
  - 1000 BTUs per hour = 0.293 kW
  - Current US renewable E in 2011: 11.7 %

US Energy use

- What is available
- US Energy use

US Renewable use

- Energy consumption by source vs. real GDP
- 1845-2001
We need to explore alternate Energy

- **Oil Reserves**
  - US has ~80 billion barrels
  - We use 25% of world production (6 billion / yr)
  - Lifetime
    - Of the top 17 oil producers only Canada, Venezuela have lifetimes > 115 yr
- **Natural Gas (25% US Energy)**
  - 200 trillion cubic feet (TCF)
  - Use: 20 TCF / year
  - Lifetime
    - a few decades left

Lunar Resources

- **Lunar History**
  - Collisional formation & melting → magma ocean
  - Differentiation
  - Light minerals (plagioclase) to surface
- **Basin formation**
  - Lava eruption (3.8-3.3 Gy)
  - Rich in Fe and Ti in basins
- **Reduced Impacts**

Other Lunar Components

- **Apollo Rock types**
  - KREEP
    - K = potassium
    - REE = rare earth elements
    - P = phosphorus
  - Orange soil (Apollo 17)
    - High volatile concentration
    - S, Zn, Pb
  - Volatiles → rare on moon
    - Solar wind implantation
    - N 50-150 ppm
    - H 2-60 ppm
  - Asteroid Debris
    - Metals 1000 ppm
- **Lunar Minerals**
  - Pyroxene [Ca,Mg,Fe]SiO$_3$
  - Plagioclase CaAl$_2$Si$_2$O$_8$
  - Olivine [Mg,Fe]$_2$SiO$_4$
  - Ilmenite FeTiO$_3$

Lunar Regolith as Shielding

- **Economics:** Must get shield material from space:
  - Shuttle cargo bay example
    - 3 m diameter, 15 m long
    - Shield to equivalent 1 Earth atm
      - 1 kg / m$^2$
    - 1500 tons shielding
    - 50 shuttle flights (destroy O$_3$)
      - $1.5$ Billion per launch
      - $75$ billion to launch “shelter”
- **What is needed?**
  - No specific material → just mass
  - Best to get material out of smaller gravity well → the moon

Lunar Concrete

- **Terrestrial Cement**
  - Good heat resistance
  - Easy to cast
  - High abrasion resistance
  - Moderate strength
- **Cement Composition**

| 65% CaO | Calcium oxide – rich in limestone. |
| 23% SiO$_2$ | silica |
| 4% Al$_2$O$_3$ | alumina |
| < 1% | Other organic compounds |

- **Process of manufacture**
  - Burn CaO (limestone) & sand → calcium silicate pebbles (clinker)
  - Grind clinker to um dust
  - Mix dust with H$_2$O
  - This hardens to cement

Alternative Processes to make Shielding

- **Melt lunar materials**
  - Focussed sunlight melts basalt at 700-1000K
  - Melt over mounds → scoop out interior materials
  - Production of glass bricks for building
  - Problem: Susceptible to cracking (brittle)
- **Microwave sintering**
  - Welds grains at contact points
  - Porous, light material
  - Needs to be sealed to hold pressure
  - AlO powder sintered at 1700°C for 2.5 min, 6 min
Concrete from the Moon

Lunar Oxygen

- Extraction Process
  - Heat ilmenite to 800°C with H₂ gas
  - FeTiO₃ + H₂ → TiO₂ + Fe + H₂O
  - H₂ – bring from Earth
  - Fe – construction use
  - H₂O Electrolysis → H₂, O
  - Recover H₂
  - O used for LOx
  - Cost ~5000 cal / gm O

- Alternate method
  - Melt regolith
  - Electric current –
    - collect O at anode
    - Cathode – metal rich alloy
  - 30,000 cal / gm O

- Oxygen is 42% by mass in lunar regolith
- Takes less E to break bonds in ilmenite

LunOx Industry

3He from Lunar Regolith

- ³He rare He isotope on Earth
  - Regolith: 10⁻¹⁵⁻¹⁰²⁰ atoms/cm³
  - Origin is solar wind implantation
  - Concentrated in ilmenite deposits
  - Nuclear fuel – no radioactive waste
  - Conventional fuels: 80% radioactive waste

- Value $4 billion/ton

Water on the Moon

Clementine Mission Profile
- Launch 1/25/94, End 5/7/94
- Map the moon in UV, Vis, near IR, Radar

Results
- Aitkin Basin (2500 km, 12 km deep)
- 15,500 km² permanently dark (T ~ 40-50K)
- Radar ice signatures → Ice 10⁻¹ m thick (sm lake)

Lunar Prospector: Discovery mission #2
- Neutron spectrometer
  - Neutrons scatter differently off water (H)
  - Effective for upper 0.5 meter of regolith

- Definitive signature of water
- Surprising: gardening remove ice! → comet impact supply?

Clementine Mineralogy
**Example of Remote Prospecting**

- How deep is an ilmenite (FeTiO₃) deposit we might use for LOx extraction?
- Ilmenite map → rich in craters
- Measure diameter of smallest craters with ilmenite
- Use depth-diameter relation
  - Larger craters penetrate deeper
  - This gives depth of mineral

**Asteroid Compositions vs Distance**

- Materials
  - O, C, S, N
- Trends
  - More processed – closer to sun
  - More primitive (water rich) farther away

| H, O | 20% water, 2% H |
| C   | 0% organic matter |
| N   | 0.1% N (polymers) |
| S   | 6% organic & elemental |
| Rare | Cl, F abundant |

**Asteroid Resources**

Location, location, Location . . .

- Most are between Mars & Jupiter
- Resonances → delivery to Earth
  - When period of one body is an even multiple of another
  - Objects "meet" at same place in orbit
  - This enhances gravity perturbations
  - Knocks objects out of orbit
- Interesting groups for proximity
  - Amors – Mars orbit crossing, outside Earth orbit
  - Apollos – Earth crossers
  - Atens – Inside Earth orbit

**Metal Extraction**

- Lunar Metals
  - Rare
    - Mond Process
      - Reacting regolith with CO at 400-500K
      - Produces pure Fe, Ni
      - Economical
  - Asteroids
    - Differentiated cores → metallic asteroids
    - Mond process
    - Transport to Earth?

- Asteroids vs. the Moon

  - Water Extraction
    - Heating 250-300°C
    - Uses 10% E needed on moon for ilmenite
    - Hydrogen
      - Moon → require H₂ from Earth
      - Asteroids provides 0.125 tons H₂ per ton of material
  - Nitrogen
    - Found in primitive asts
    - Not found on moon
    - Recovered using O₂ and H₂ gas
    - Byproduct: CH₄ (fuel)
  - Metals
    - Low abund on Moon
    - Economic advantage for asteroids
Economics – Consider $\Delta v$

- $\Delta v$ at LEO → escape trajectory
- $\Delta v$ at arrival – match asteroid orbit $v$
- $\Delta v$ to land (small, low gravity)
- $\Delta v$ to take off (small)
- $\Delta v$ to initial Earth intersect trajectory
- Aerobraking at Earth to slow $v$
- Small $\Delta v$ to lift perigee from Earth atm and match space station velocity
- Launch windows
- Transport time

<table>
<thead>
<tr>
<th>Body</th>
<th>$\Delta v$</th>
<th>Time of Flight</th>
<th>$\Delta v$</th>
<th>Time of Flight</th>
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<tbody>
<tr>
<td>Asteroids</td>
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<tr>
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<td>270 days</td>
<td>0.00 km/s</td>
<td>270 days</td>
</tr>
</tbody>
</table>

*All values in $\Delta v$ are non-zero. Asteroids in the Sun system are also non-zero because of the solar environment.*

LUNAR FERRY OPERATIONS

- Launch windows
- Transport time

LUNAR MISSILE DESIGN /

AEROSPACE...

NASA