Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration*

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Abstract

NASA and US Government-sponsored research established the baseline working knowledge and systems for space exploration and continue to make important contributions to US National and to worldwide space exploration activities. We are in a transition period now, where private commercial interests and public-private partnerships are assuming more of the leadership in space activities and in research to support all aspects of space business. It is important to recognize the historically critical importance of NASA and US sponsored research, but the expansion of private activities following NASA initiatives is becoming more important. As an example, the support of the International Space Station by private supply missions illustrates the expansion of private industry into this once exclusively government task. How has private industry leveraged this activity to expand their capabilities, and how will this opportunity be leveraged by private industry to create a broader-based commercial space sector? We examine, from a qualitative standpoint, the various activities that are being driven by actual and planned commercial space activities, and then provide an initial quantitative assessment of returns for private businesses. The scope of this assessment begins with publicly announced efforts to return commercial quantities of rare earth elements and precious metals from metallic asteroids, and then focuses on the “found” value of supporting materials, such as ice, building materials, such as iron, and regolith, such as dust that can be used as shielding and formed into bricks for walls or mass for shielding. Incidental to the high-valued opportunities related to metallic asteroids, our initial conclusions indicate that ice acquisition and use in situ for life-supporting atmosphere, fuel supply and production of energy from uninterruptable solar energy collectors may be as important as focusing on capturing metallic asteroids. As a comparison with historical precedent, consider the businesses that supplied the gold mining efforts in California during the 1800s; more consistent and long-lived businesses were established from providing supplies to the miners than were made by the miners.

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Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration

Making Space Exploration Affordable

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Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration

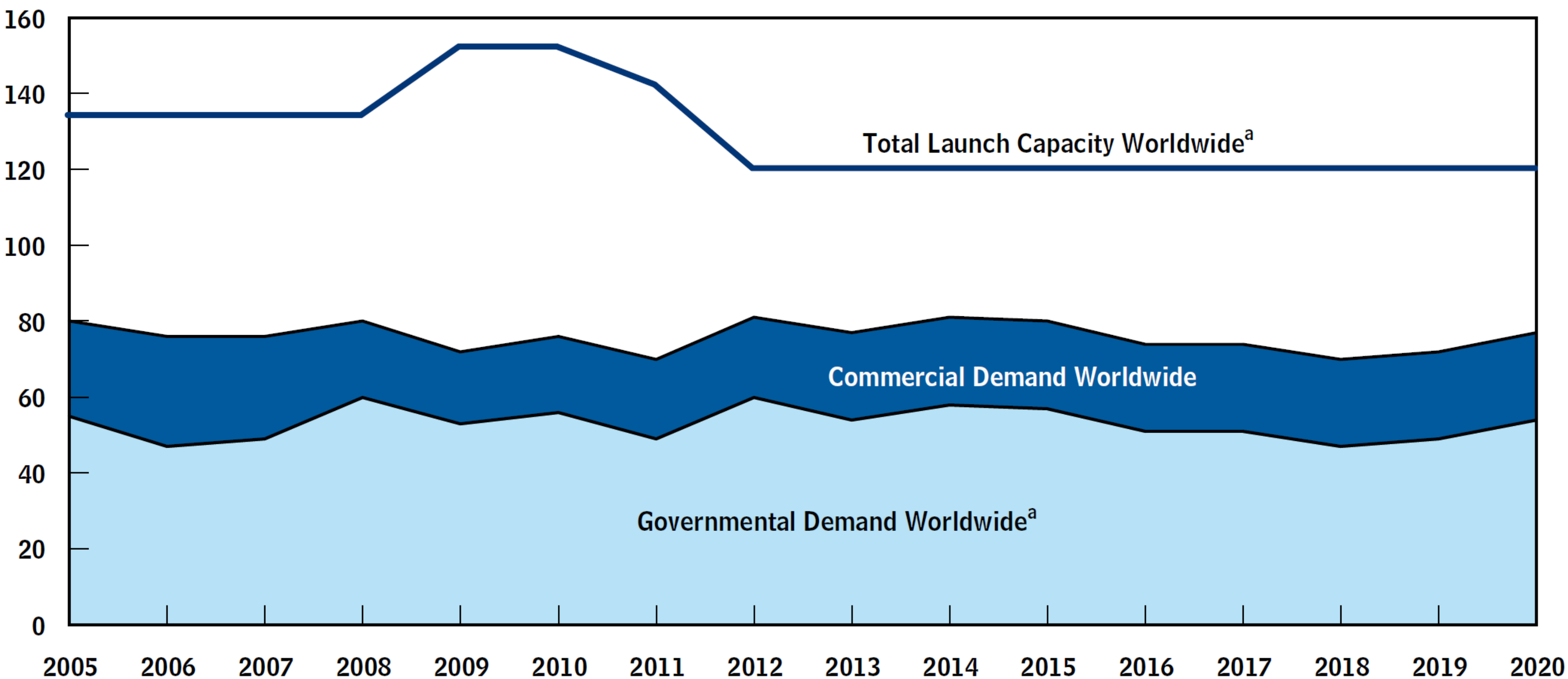
We know ISRU is practical, when and where is it profitable?

1. In Orbit;
    1. Fuel Depot, using residual fuel from other launches
    2. Fuel Depot, using manufactured fuel from Lunar or Asteroid sources; ice as primary resource
    3. Solar-Power Satellites, manufactured from space-based materials
    4. Communications, Satellite Maintenance, monitoring and reporting
2. Lunar
    1. Ice-derived H_2, O_2, LOX
    2. Minerals and Metals, KREP, REE, Ti, Thorium
    3. Power Generation, H-3 and H-3 export to earth
    4. Monitoring, maintenance and observation
3. Near-earth Asteroids and / or Mars
    1. High-value REE
    2. Water-Ice and other volatiles
    3. Kerogen-based materials
    4. Aluminum, iron, nickel, cadium and other building materials

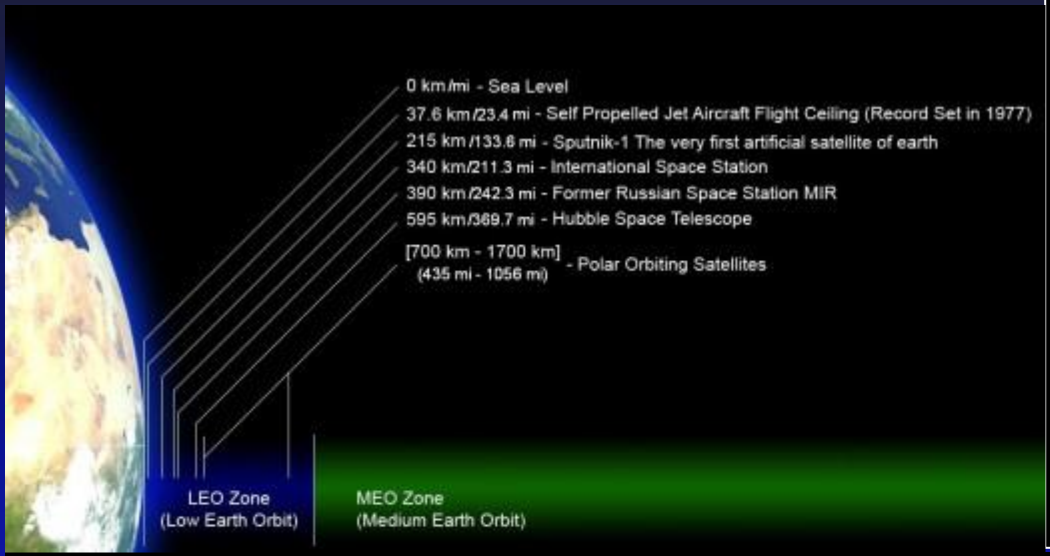
Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration

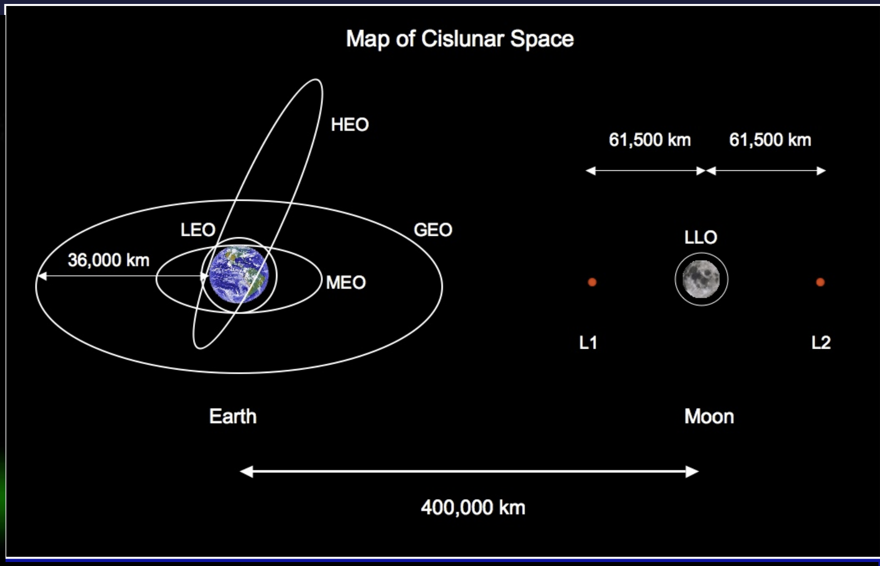
Worldwide Capacity and Demand for Launch Services

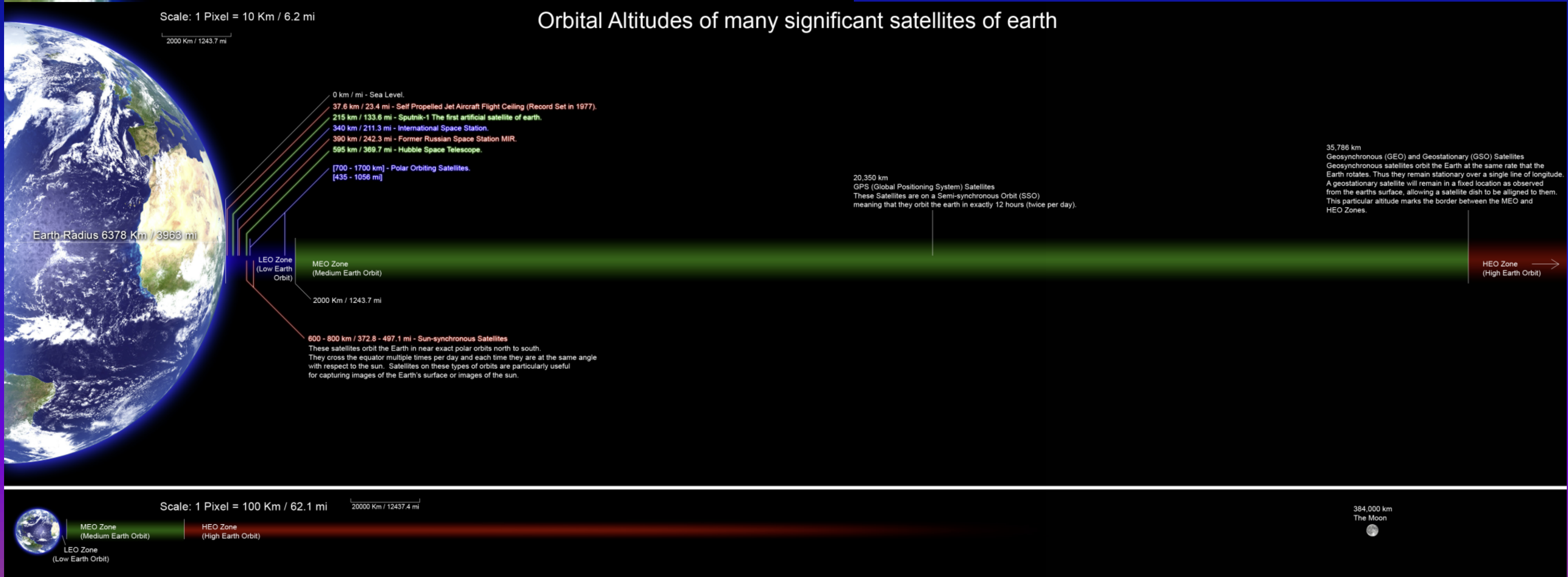
(Number of launch vehicles)



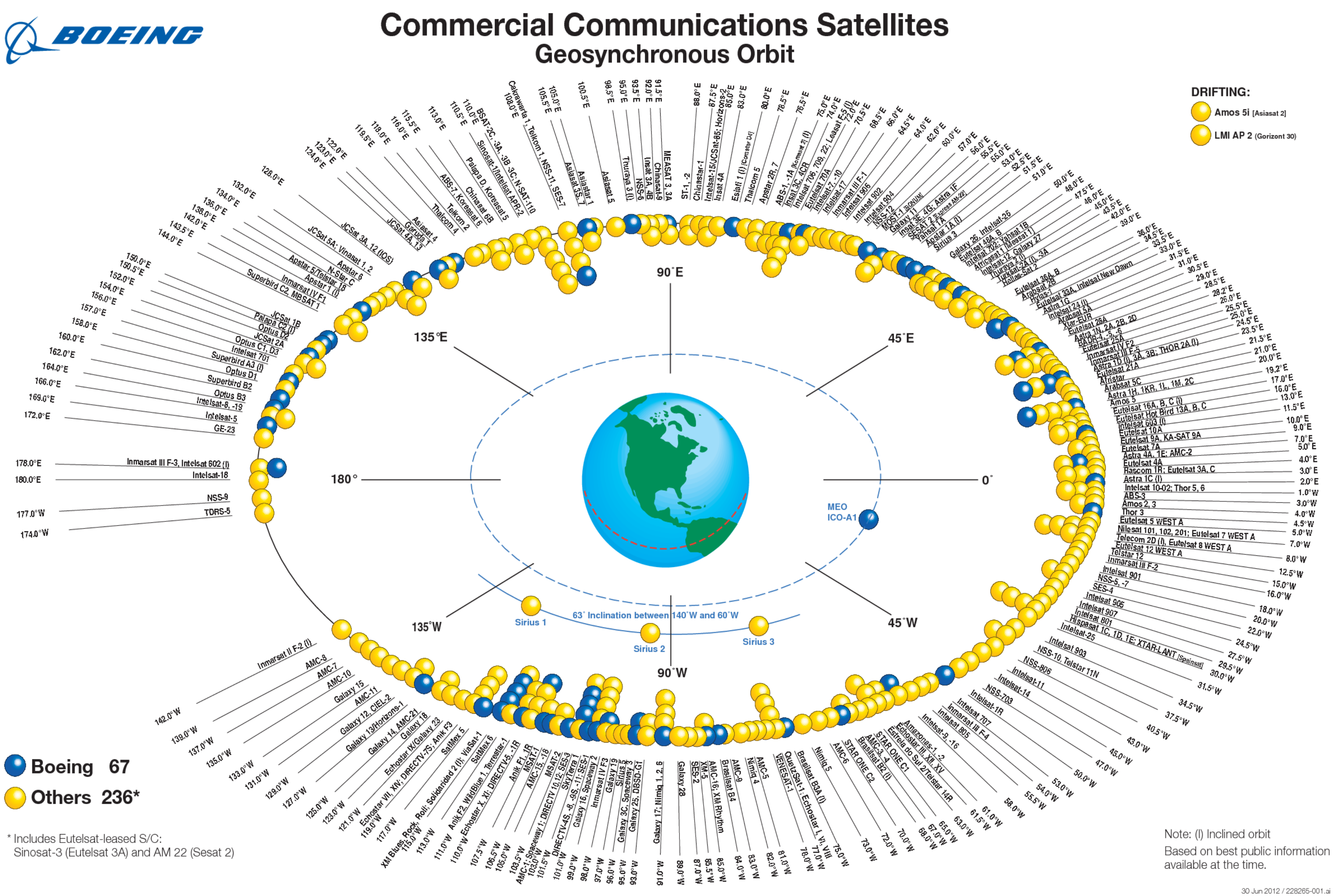
Source: Congressional Budget Office based on data provided by the Federal Aviation Administration and the Futron Corporation.


0 km /mi - Sea Level
37.6 km /23.4 mi - Self Propelled Jet Aircraft Flight Ceiling (Record Set in 1977)
215 km /133.6 mi - Sputnik-1 The very first artificial satellite of earth
340 km/211.3 mi - International Space Station
390 km /242.3 mi - Former Russian Space Station MIR
595 km /369.7 mi - Hubble Space Telescope
[700 km - 1700 km] (435 mi - 1056 mi) - Polar Orbiting Satellites
LEO Zone (Low Earth Orbit)
MEO Zone (Medium Earth Orbit)


Map of Cislunar Space
HEO
LEO
GEO
MEO
36,000 km
61,500 km
61,500 km
LLO
L1
L2
Earth
Moon
400,000 km


Scale: 1 Pixel = 10 Km / 6.2 mi
2000 Km / 1243.7 mi
Orbital Altitudes of many significant satellites of earth
0 km / mi - Sea Level.
37.6 km / 23.4 mi - Self Propelled Jet Aircraft Flight Ceiling (Record Set in 1977).
215 km / 133.6 mi - Sputnik-1 The first artificial satellite of earth.
340 km / 211.3 mi - International Space Station.
390 km / 242.3 mi - Former Russian Space Station MIR.
595 km / 369.7 mi - Hubble Space Telescope.
[700 - 1700 km] - Polar Orbiting Satellites.
[435 - 1056 mi]
20,350 km
GPS (Global Positioning System) Satellites
These Satellites are on a Semi-synchronous Orbit (SSO)
meaning that they orbit the earth in exactly 12 hours (twice per day).
35,786 km
Geosynchronous (GEO) and Geostationary (GSO) Satellites
Geosynchronous satellites orbit the Earth at the same rate that the
Earth rotates. Thus they remain stationary over a single line of longitude.
A geostationary satellite will remain in a fixed location as observed
from the earths surface, allowing a satellite dish to be alligned to them.
This particular altitude marks the border between the MEO and
HEO Zones.
Earth Radius 6378 Km / 3963 mi
LEO Zone (Low Earth Orbit)
MEO Zone (Medium Earth Orbit)
HEO Zone (High Earth Orbit)
2000 Km / 1243.7 mi
600 - 800 km / 372.8 - 497.1 mi - Sun-synchronous Satellites
These satellites orbit the Earth in near exact polar orbits north to south.
They cross the equator multiple times per day and each time they are at the same angle
with respect to the sun. Satellites on these types of orbits are particularly useful
for capturing images of the Earth's surface or images of the sun.
Scale: 1 Pixel = 100 Km / 62.1 mi
20000 Km / 12437.4 mi
MEO Zone (Medium Earth Orbit)
HEO Zone (High Earth Orbit)
LEO Zone (Low Earth Orbit)
384,000 km
The Moon

Opportunities in Orbit, Earth Lagrange Points, and Cis-Lunar Space



Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration

- Significant Hurdles:
  - Launch Costs: Goal is to reduce costs to $1,000/kg to $100/kg
    - Chemically Fueled rockets are about at their limit
    - External propulsion has technological barriers, e.g., Laser, rail gun, space elevator.
    - Nuclear rockets have public perceptions to overcome, but represent the only viable option at this time.

Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration

- Key issue: weight is dollars.
- Manned launch costs are 5 to 10 times greater than robotic-unmanned flights.
- Estimates for the Space Shuttle costs ranged from $15,000 to $25,000 per kilogram to low earth orbit.
- Airline freight rates are in the range of $5 to $15 dollars per kilogram.

Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration

Launch Costs to Geosynchronous Transfer Orbit

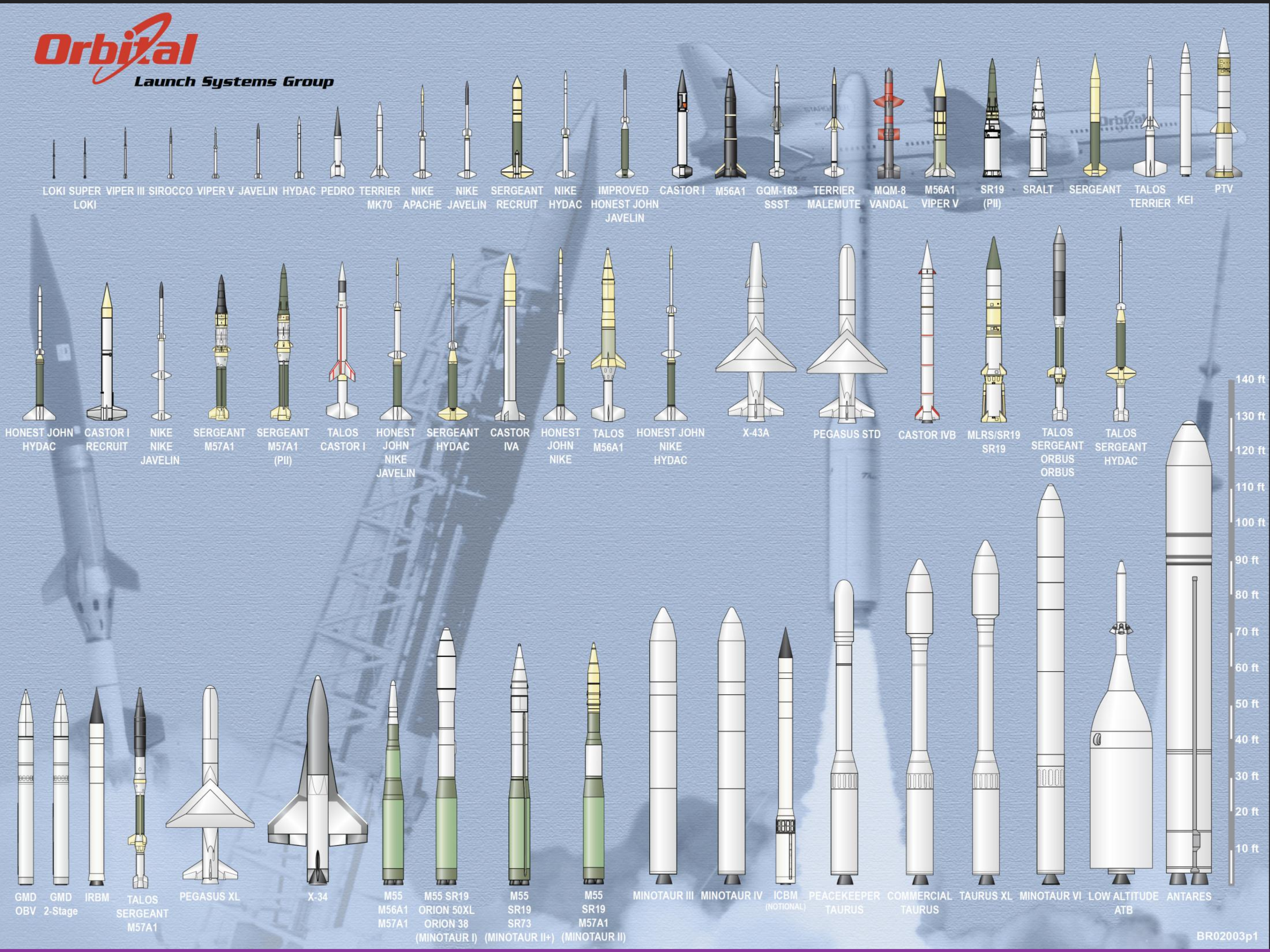
Atlas V 401: ≈ 27,777 *US$/kg GTO*

Delta IV Heavy: ≈ 25,424 *US$/kg GTO*

Ariane 5 ECA: ≈ 24,079 *US$/kg GTO*

Ariane 5 ES: ≈ 30,249 *US$/kg GTO*

Proton-M: ≈ 16,620 *US$/kg GTO*



Orbital
Launch Systems Group
LOKI
SUPER LOKI
VIPER III
SIROCCO
VIPER V
JAVELIN
HYDAC
PEDRO
TERRIER MK70
NIKE APACHE
NIKE JAVELIN
SERGEANT RECRUIT
NIKE HYDAC
IMPROVED HONEST JOHN JAVELIN
CASTOR I
M56A1
GQM-163 SSST
TERRIER MALEMUTE
MQM-8 VANDAL
M56A1 VIPER V
SR19 (PII)
SRALT
SERGEANT
TALOS TERRIER
KEI
PTV
HONEST JOHN HYDAC
CASTOR I RECRUIT
NIKE NIKE JAVELIN
SERGEANT M57A1
SERGEANT M57A1 (PII)
TALOS CASTOR I
HONEST JOHN NIKE JAVELIN
SERGEANT HYDAC
CASTOR IVA
HONEST JOHN NIKE
TALOS M56A1
HONEST JOHN NIKE HYDAC
X-43A
PEGASUS STD
CASTOR IVB
MLRS/SR19 SR19
TALOS SERGEANT ORBUS ORBUS
TALOS SERGEANT HYDAC
GMD OBV
GMD 2-Stage
IRBM
TALOS SERGEANT M57A1
PEGASUS XL
X-34
M55 M56A1 M57A1
M55 SR19 ORION 50XL ORION 38 (MINOTAUR I)
M55 SR19 SR73 (MINOTAUR II+)
M55 SR19 M57A1 (MINOTAUR II)
MINOTAUR III
MINOTAUR IV
ICBM (NOTIONAL)
PEACEKEEPER TAURUS
COMMERCIAL TAURUS
TAURUS XL
MINOTAUR VI
LOW ALTITUDE ATB
ANTARES
140 ft
130 ft
120 ft
110 ft
100 ft
90 ft
80 ft
70 ft
60 ft
50 ft
40 ft
30 ft
20 ft
10 ft
BR02003p1

Economic Benefits of In Situ Resource Utilization in Near-Term Space Exploration

First task is improvement in launch systems

"Nuclear DC-X [LANTR] has such far-reaching capabilities that it represents a new and vital way of realizing the benefits of space. This advanced propulsion concept can be implemented within 5 years to meet all manned and unmanned space mission requirements." (Davis, 2004; pg. 54)

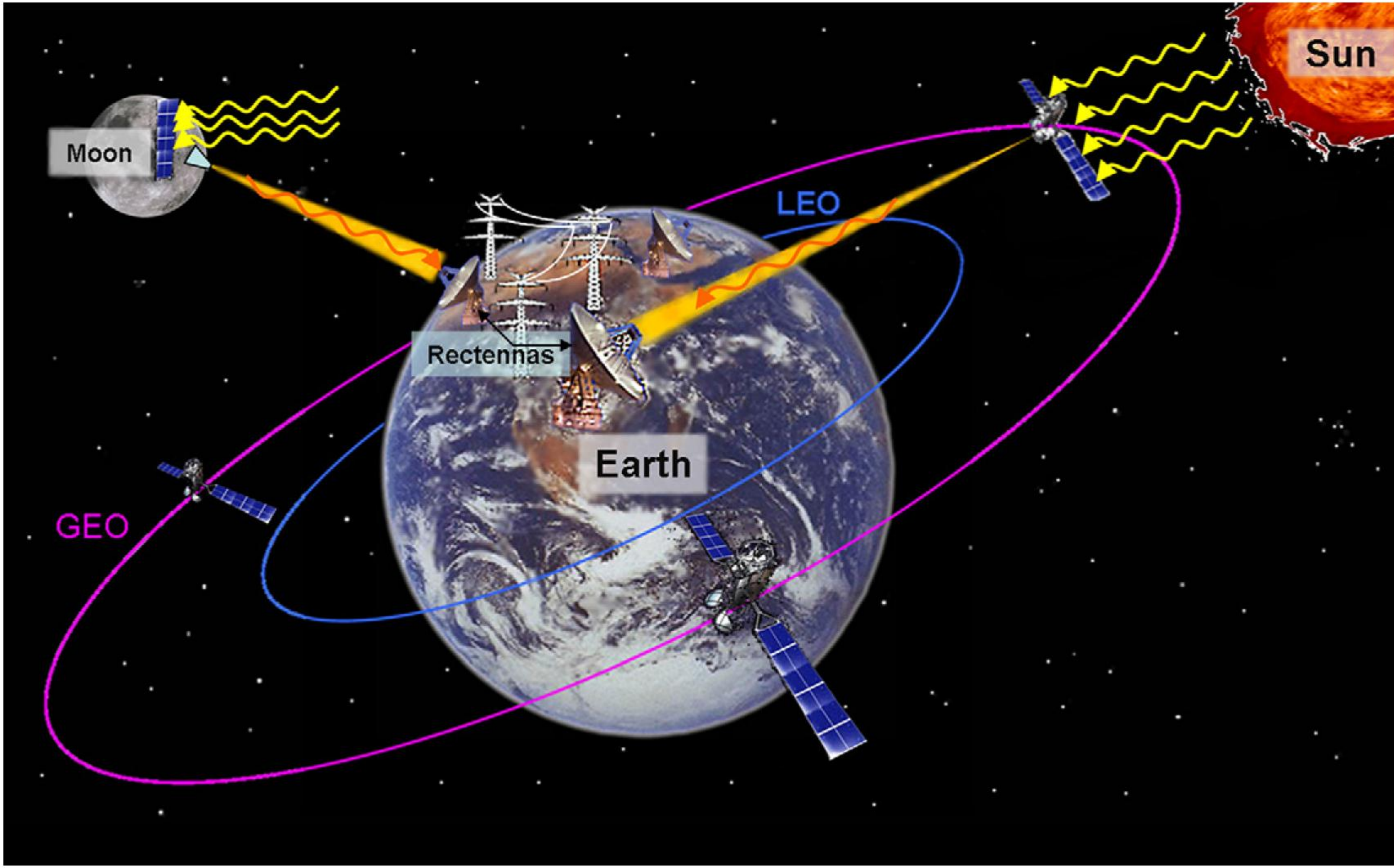
Historical and Existing Launch Systems	Minimun Cost $/KG
Rockot	$10,000
Shuttle	$12,000
Athena 2	$12,000
Taurus	$20,000
ISS, Commercial	$22,000
Pegasus XL	$24,000
Long March CZ-2C	$30,000
Athena 1	$41,000

Innovative, Near Term, Alternative Launch Systems	Projected Cost Range $/KG	
Laser Ablative Launch	$100	$300
Nuclear Thermal Rocket	$150	$500
Space Elevator	$50	$150
Air Breathing Rockets	$200	$500
Magnetic Levitation Launch Assist	$30	$100
Pulse Detonation Engines	$500	$1,000

modified after Phipps, C. R., Reilly, J. P., and Campbell, J. W., 2000

	Launch Cost	Mass (kg) to LEO	Cost per kg to LEO	Mass (kg) to GTO	Cost per kg to GTO
Falcon 9	$56,500,000	13,150	$4,297	4,850	$11,649
Falcon Heavy (< 6.4 T to GTO)	$77,100,000	53,000	$1,455		
Falcone Heavy (> 6.4 T to GTO)	$135,000,000			21,200	$6,368

Illustration and text captured from SpaceX Website:
www.spacex.com March 26th, 2104)



Space solar power systems. Latest assessments indicate power cost to be in the range of 12 to 18 cents per kilowatt hour. Average retail price of electricity for Texas during 2012 was 9.56 cents per kilowatt hour.

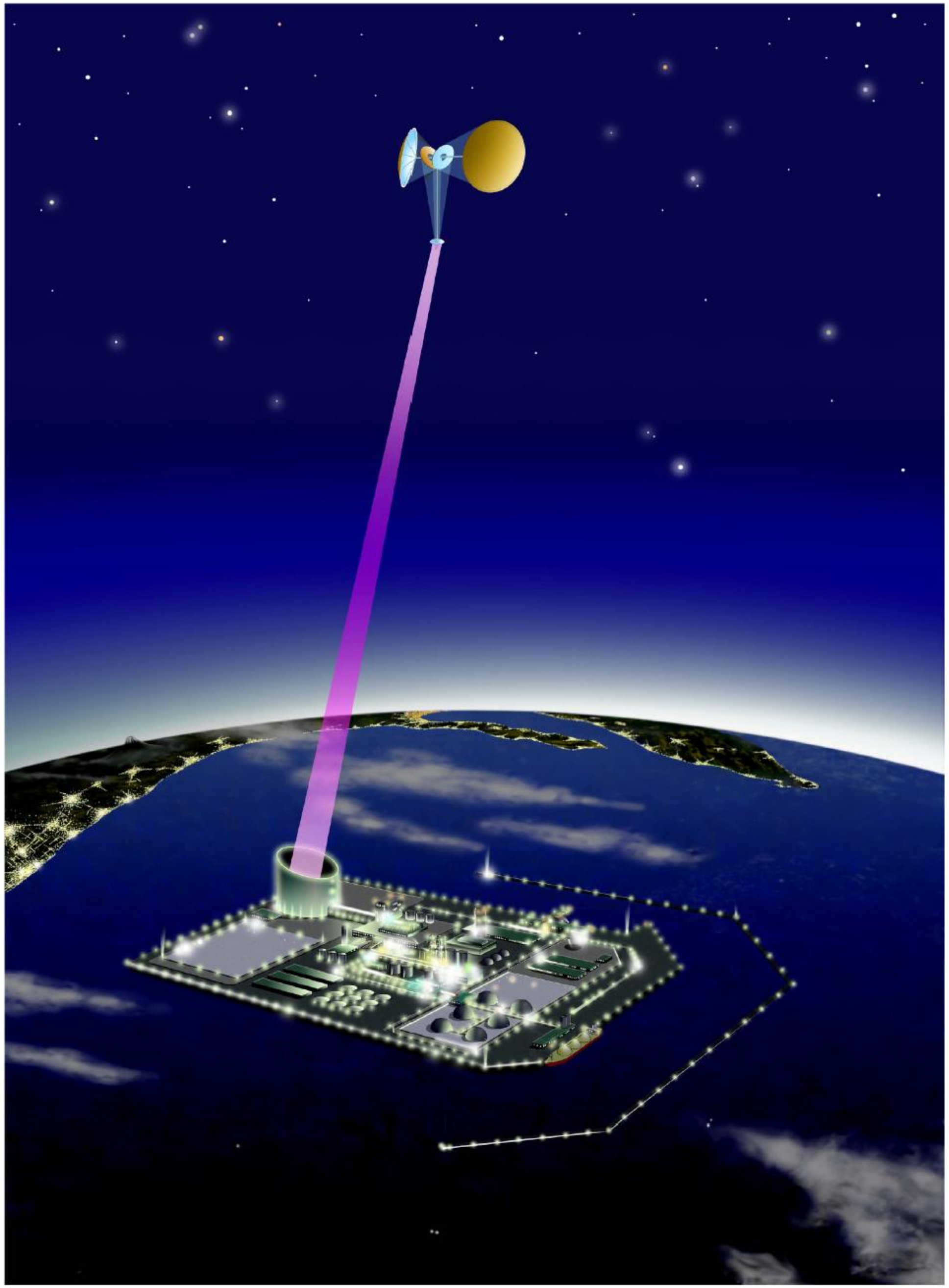


FIG. 7: JAXA L-SPS system diagram. (source: JAXA)

Japan Space Agency (JAXA) is aggressively working on Space-based Solar Power Stations and the potential of Helium-3 recovery from the Lunar Regolith.

Transmission of energy via MASER, LASER or microwave transmission is an issue.

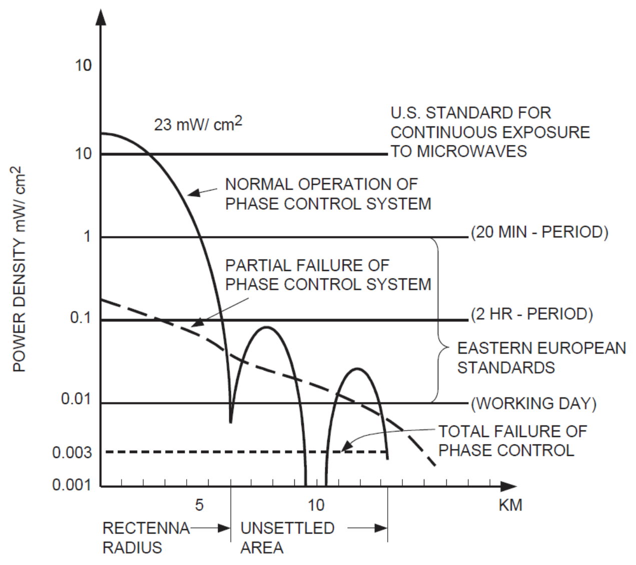


Fig. 4. International standards for continuous microwave radiation exposure.

Fig. 5. Ground receiving rectenna (artist's view).

Installed Cost ≈ Range $1,000 to $2,700 /KW

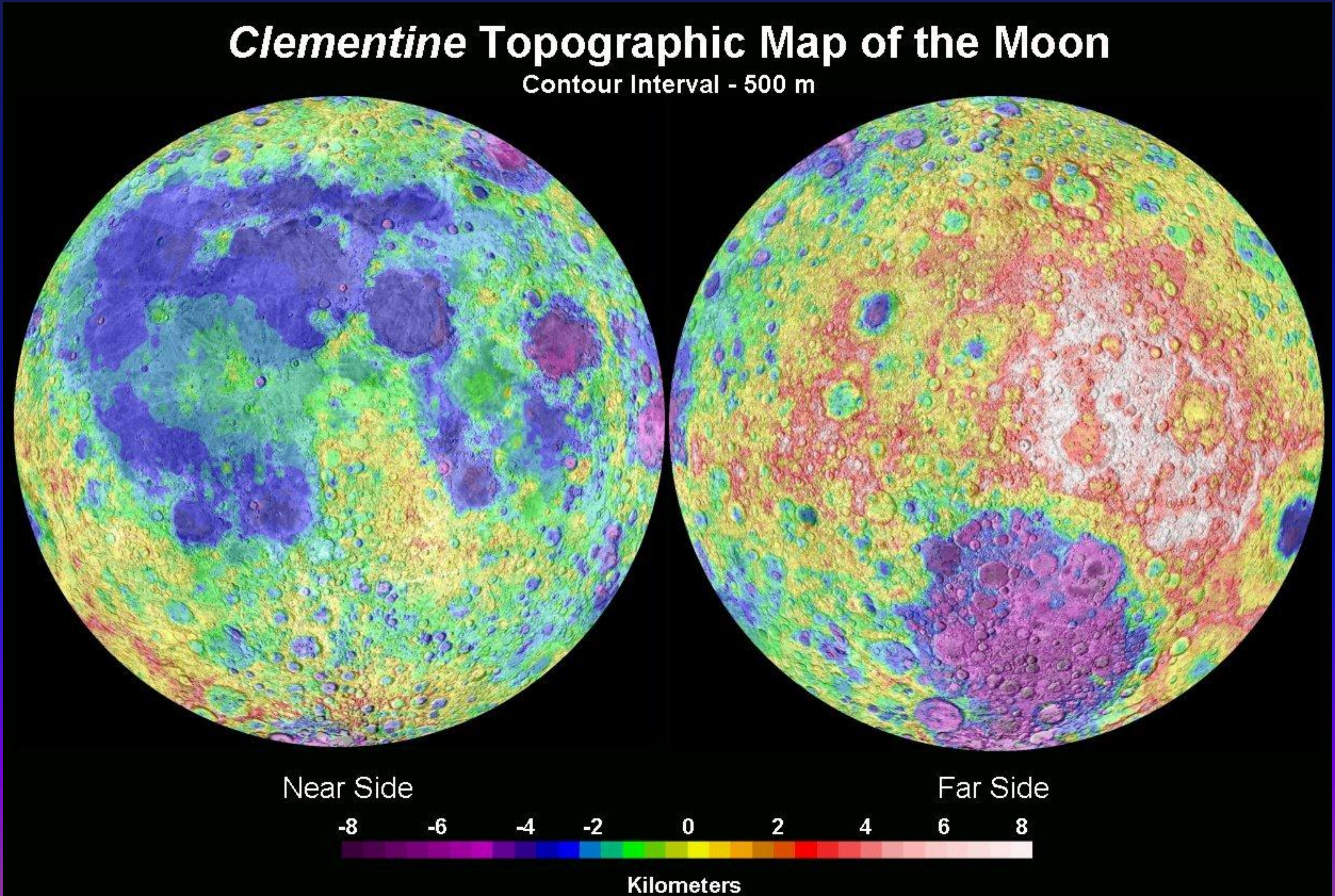
Production (wholesale) Cost ≈ $0.05-0.07 /KWhr

(Glaser, P. 1993)
(Seboldt, W. 2004, Criswell, 2013)

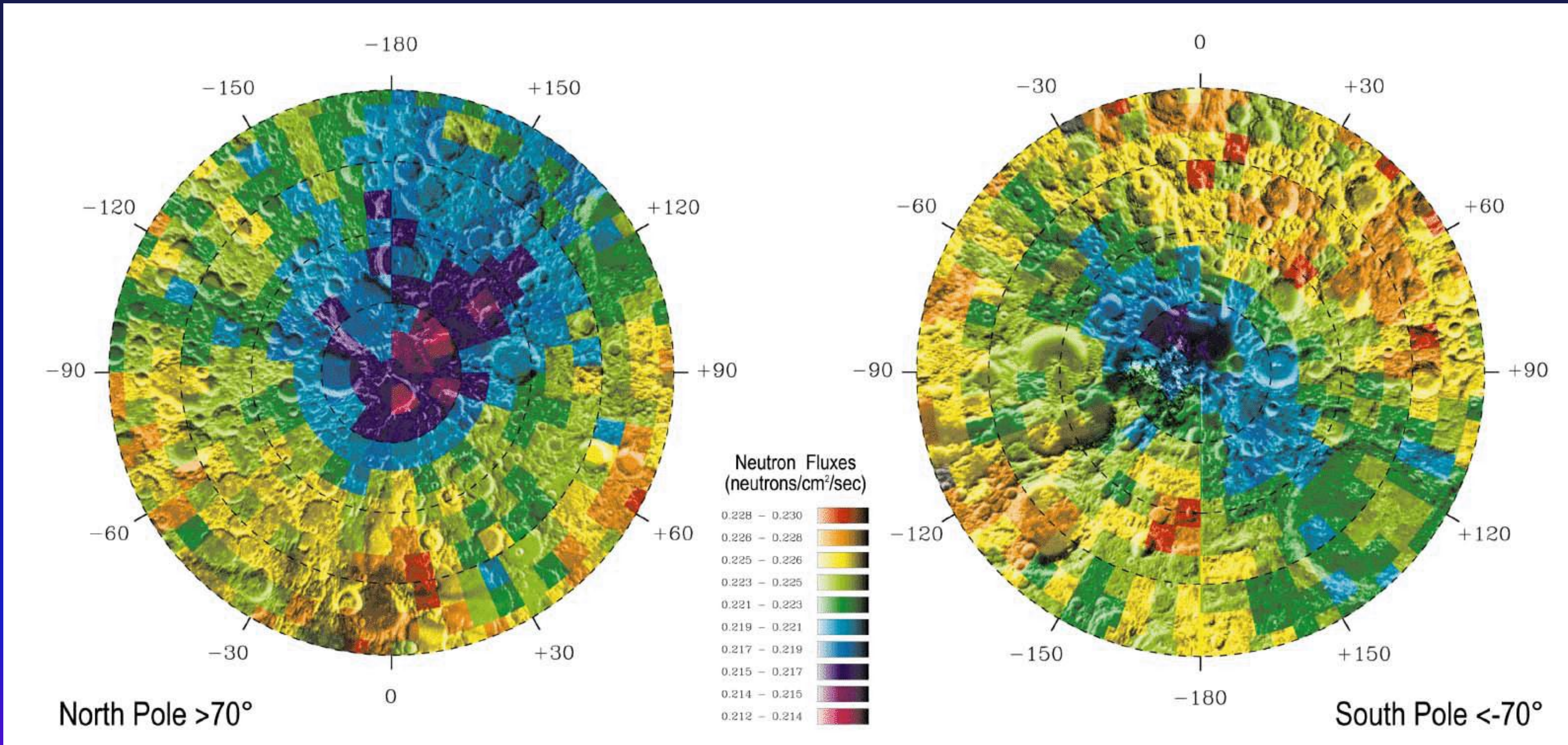
Why return to the moon?

We need to live and work in space, the International Space Station has been a great experience, but by implication, our next stops are either or both the Asteroids or Mars. Both of these destinations have elements that have not been explored, evaluated or tested aboard the ISS. We need to learn how to live and work on the surface of a low-gravity body with limited to no atmosphere, and hostile radiation environments. The moon is still within range of an emergency supply mission, but it provides all of the test environments necessary to evaluate additional survival aspects.

Lunar Resources



Lunar Resources



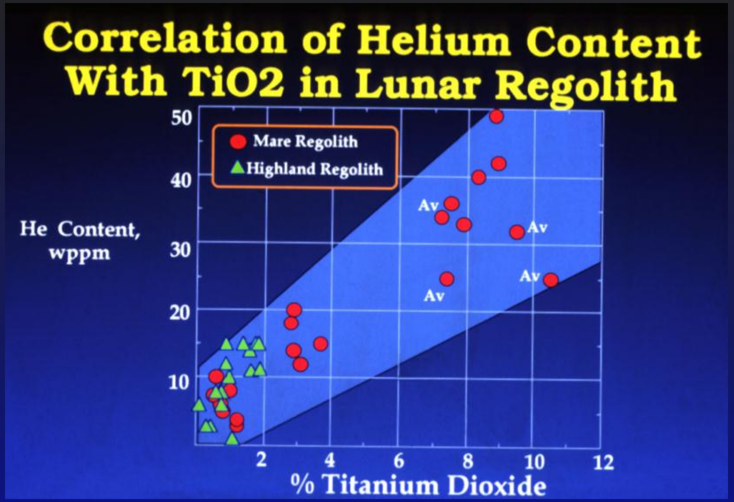
The dark blue and purple areas at the moon's poles indicate neutron emissions that are consistent with hydrogen-rich deposits covered by desiccated regolith. These hydrogen signatures are possible indications of water in the form of ice or hydrated minerals (Feldman et al., Science, 281, 1496, 1998).

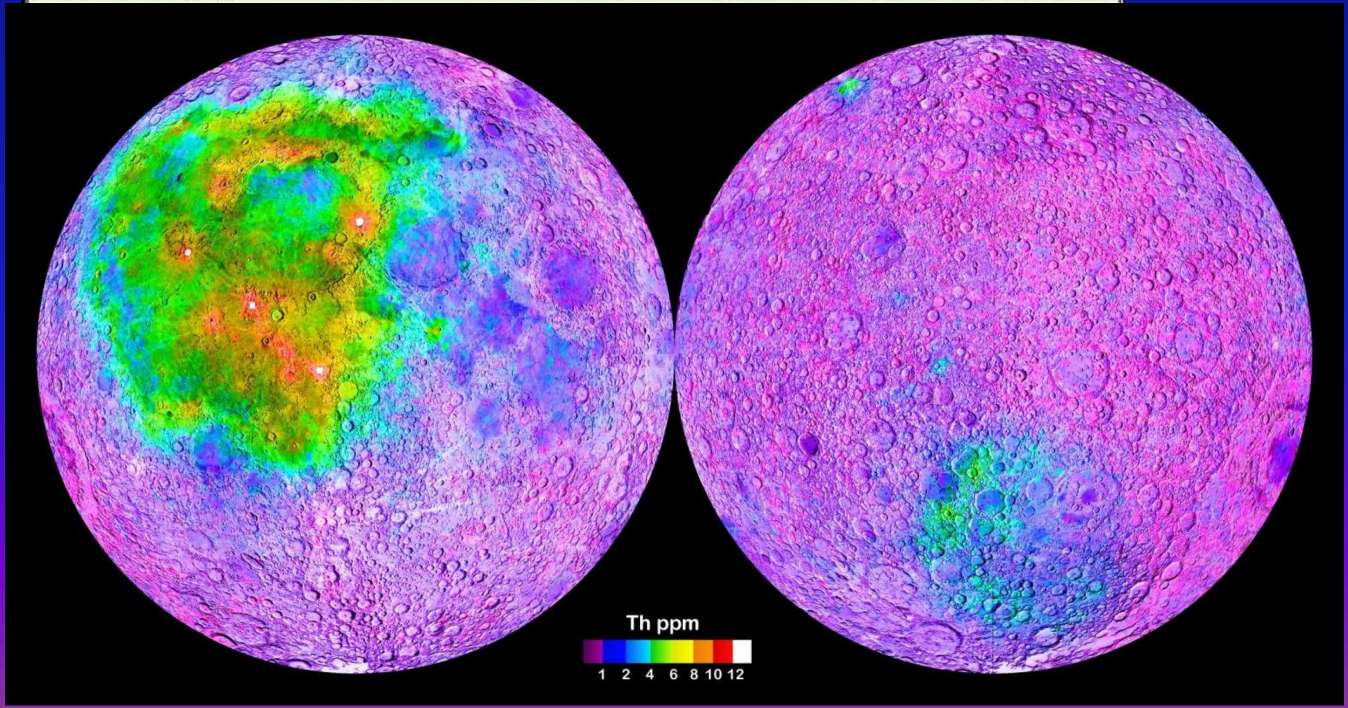
Lunar Resources

(W. Ambrose)

Resource	Use	Occurrence
Helium-3	**Energy**	**Mature regolith**
Hydrogen	**Propellant, water**	**Mature regolith, poles**
Oxygen	**Propellant, air/water**	**Global**
Nitrogen, carbon	**Food and plastics**	**Breccias/regolith**
Metals/bulk regolith **Iron** **Titanium** **Aluminum**	**Construction** **Moon base** **Shielding** **Roads** **Solar power facility**	**Regolith, mare**

Comparison of Terrestrial and Lunar REE Abundances	Lunar KREEP Basalt 15386 REE Abundance (ppm) typical	Apollo 16 ultra-KREEP REE Abundance (ppm) high	Bulk Continental Crust REE (ppm)	8.9% REO Mountain Pass Mine Molycorp	15.4% REO Mount Weld Mine Lynas Corp
Yttrium (Y)	240.9	na	24	70.0786	0
Lanthanum (La)	84.1	282	30	25656.9378	33493.383
Cerium (Ce)	213.1	733	60	37690.1472	61456.1825
Praseodymium (Pr)	30	na	6.7	3118.0705	7000.7476
Neodymium (Nd)	125.6	460	27	8546.5632	24427.326
Samarium (Sm)	36.5	127	5.3	690.7824	3014.7779
Europium (Eu)	2.78	5.36	1.3	76.8604	589.1652
Gadolinium (Gd)	43.9	na	4	154.4328	0
Terbium (Tb)	7.51	27.4	0.65	0	90.9807
Dysprosium (Dy)	45.7	na	3.8	0	166.3834
Holmium (Ho)	10.3	na	0.8	0	0
Erbium (Er)	28.3	na	2.1	0	0
Thulium (Tm)	3.97	na	0.3	0	0
Ytterbium (Yb)	26.2	77	2	0	0
Lutetium (Lu)	3.59	10.9	0.35	0	0
TOTAL REE (ppm)	**902.45**	Aprox 4000	**168.3**	**76003.8729**	**130238.9463**

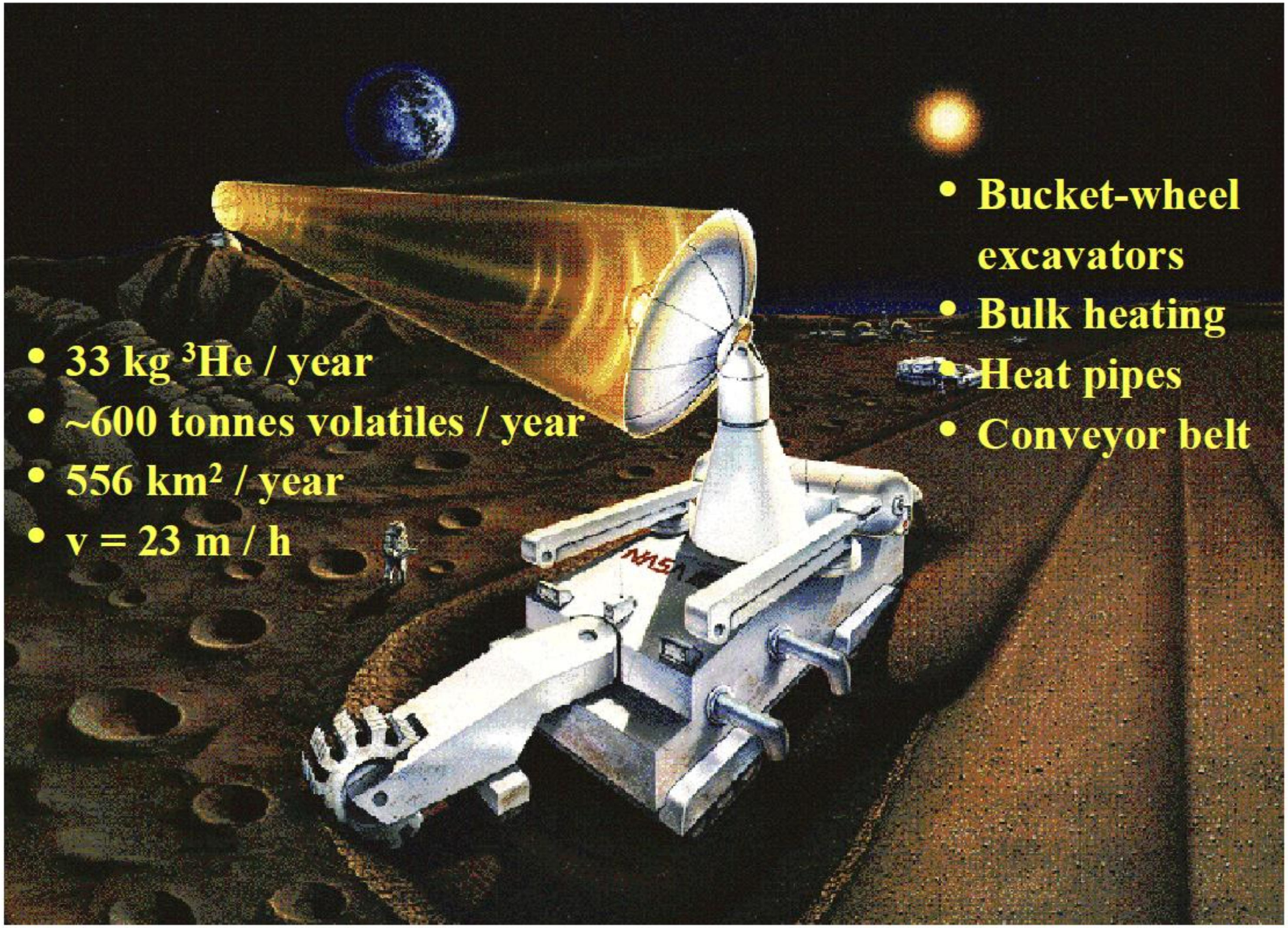




Rare Earth Elements, Helium-3 and Thorium Content of Lunar Regolith

Spudis, P. Ambrose, W.

Well-Developed Terrestrial Technology Gives Access to ~10^9 kg of Lunar ^3He



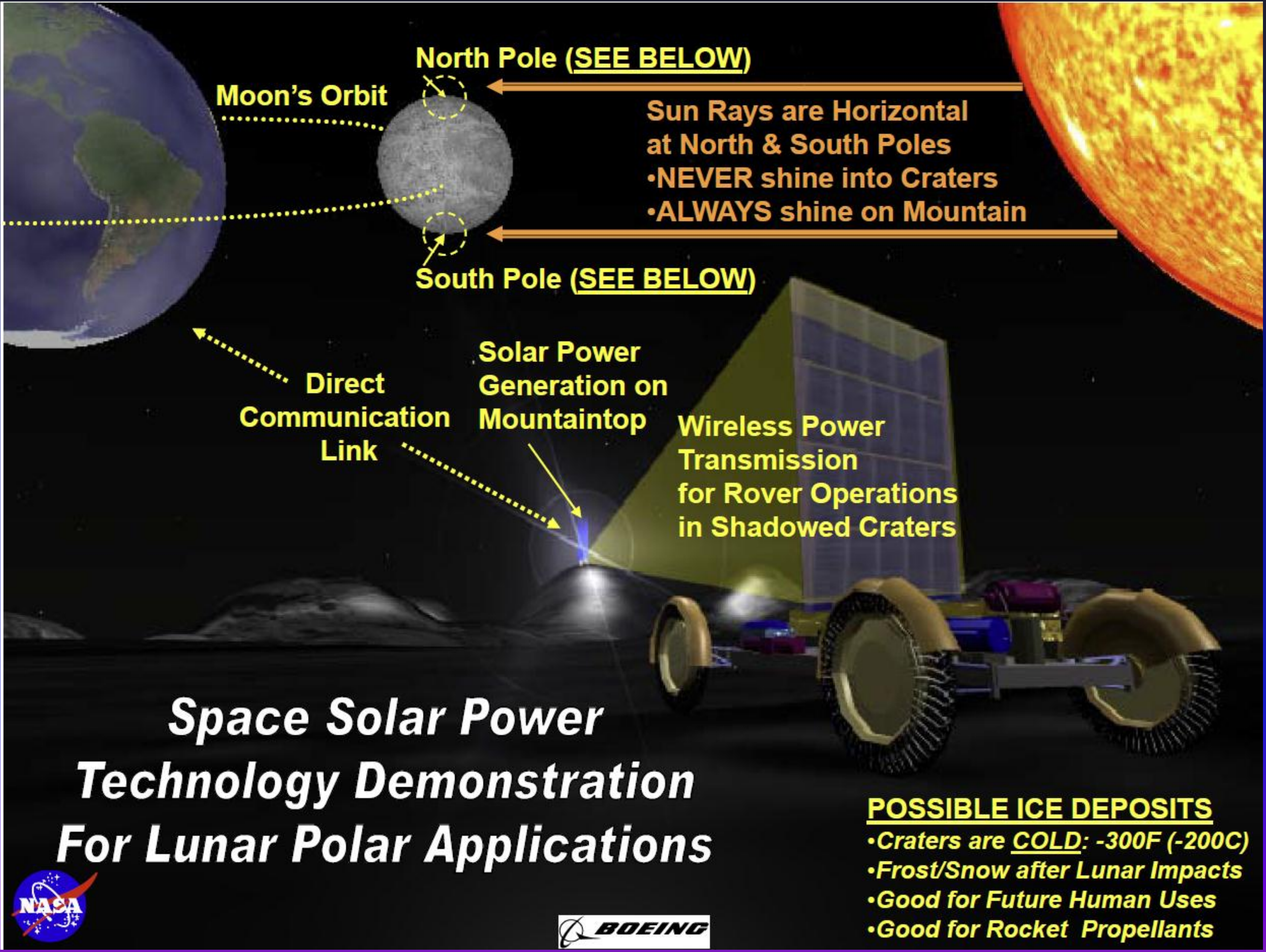
FUNDAMENTAL ASSUMPTIONS

For a 1,000 MW Helium 3 power plant

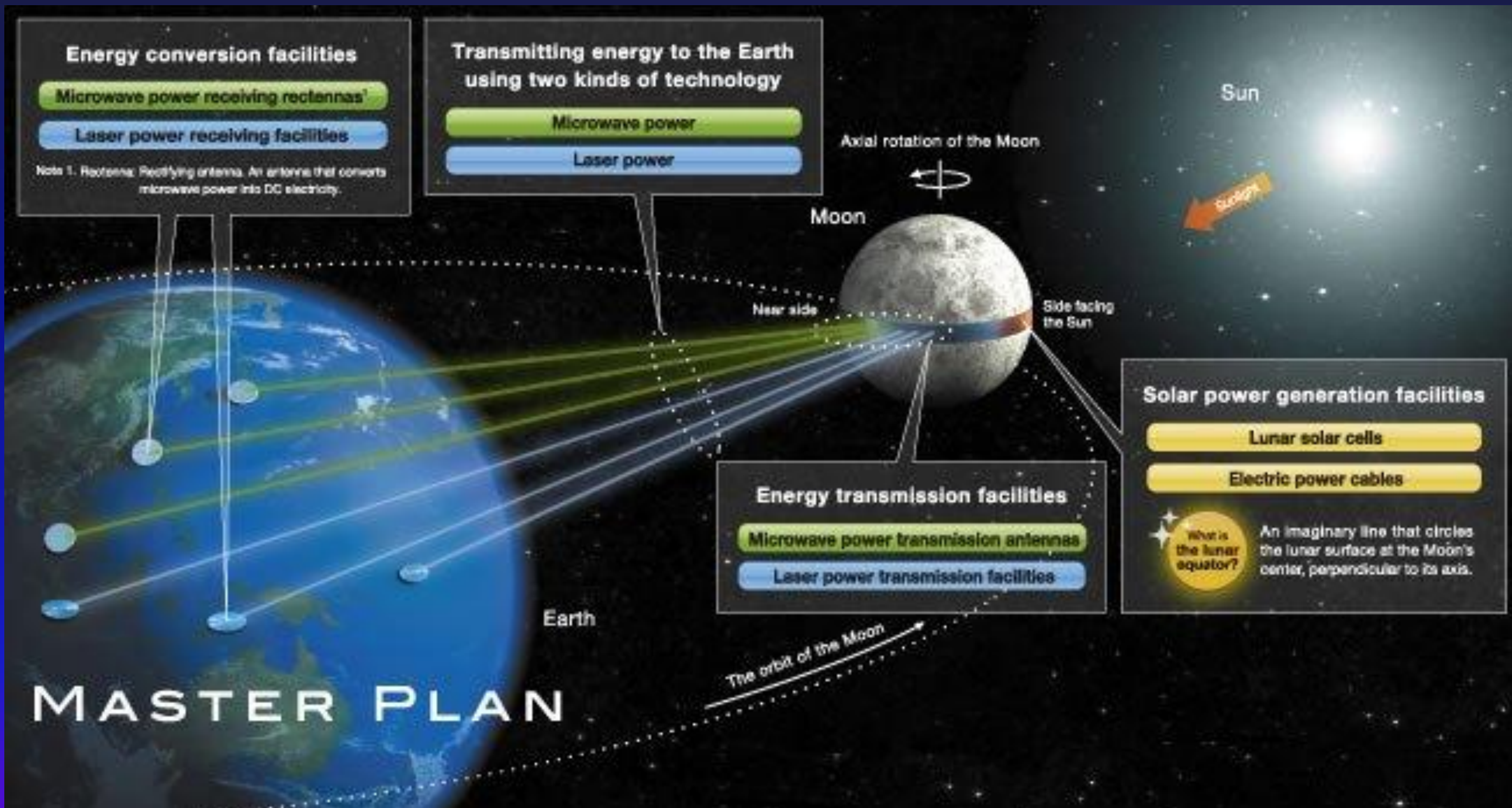
- $15 B MAXIMUM CAPITAL AVAILABLE
- <u>$140 M / 100 KG FUTURE VALUE OF HELIUM-3 (D/He-3)</u>
  - $1.27 / MILLION BTUs CURRENT COAL CONTRACT PRICE
  - $2.10 / MILLION BTUs CURRENT FUTURES CONTRACTS
  - $2.50 / MILLION BTUs ASSUMED FOR 2010-2015
  - 100 KG HELIUM-3 = 5.6 X 10^7 MILLION BTUs (D/He-3)
- $320 MILLION ANNUAL REVENUES FROM 1000 MWe PLANT
  - $0.04 / KW-HR PRICE "AT THE FENCE"

Modified from Harrison H Schmitt, NEEP Lecture 39.

Based on these assumptions, an IRR (internal rate of return) greater than 10% can be achieved with an installed capacity greater than 15 GWs. Using revised figures consistent with updated power costs and launch costs, an IRR of greater than 10% can be achieved with an installed capacity of 1,200MWs or greater. BLC


North Pole (SEE BELOW)
Moon's Orbit
Sun Rays are Horizontal
at North & South Poles
•NEVER shine into Craters
•ALWAYS shine on Mountain
South Pole (SEE BELOW)
Solar Power
Generation on
Mountaintop
Direct
Communication
Link
Wireless Power
Transmission
for Rover Operations
in Shadowed Craters
Space Solar Power
Technology Demonstration
For Lunar Polar Applications
POSSIBLE ICE DEPOSITS
•Craters are COLD: -300F (-200C)
•Frost/Snow after Lunar Impacts
•Good for Future Human Uses
•Good for Rocket Propellants
NASA
BOEING

Permanent habitations will be efficient and comfortable. They will be the new permanent home for the explorationists in our societies.



Energy conversion facilities
Microwave power receiving rectennas[1]
Laser power receiving facilities
Note 1. Rectenna: Rectifying antenna. An antenna that converts microwave power into DC electricity.
Transmitting energy to the Earth using two kinds of technology
Microwave power
Laser power
Axial rotation of the Moon
Sun
Sunlight
Moon
Near side
Side facing the Sun
Solar power generation facilities
Lunar solar cells
Electric power cables
What is the lunar equator?
An imaginary line that circles the lunar surface at the Moon's center, perpendicular to its axis.
Energy transmission facilities
Microwave power transmission antennas
Laser power transmission facilities
Earth
The orbit of the Moon
MASTER PLAN

ASTEROIDS

"NEAs may be the most attractive source of shielding, propellants, metals and refractories in orbits around the Earth." (Lewis et al., 1993)

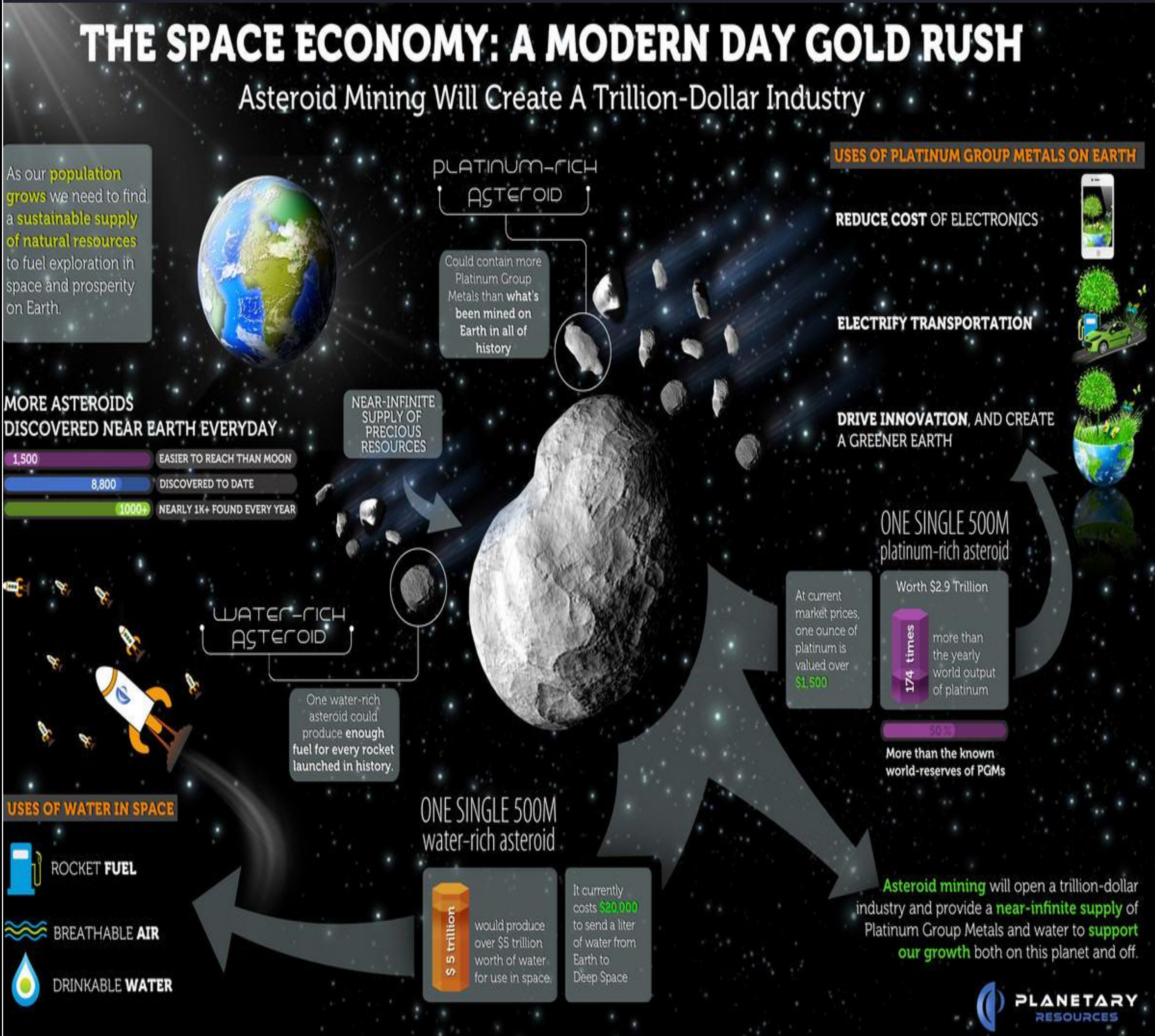
"The purpose of In Situ Resource Utilization (ISRU) is to harness & utilize these [in situ] *resources to create products & services which enable and significantly reduce the mass, cost, & risk of near and long-term space exploration."* (Sanders and Duke, 2005)

"The NEOs contain all the elements to make space exploration and resource development feasible, economically achievable, and profitable". (Cutright, B. L., 2013)

Arguments for Near-Earth Objects: Economics

- Mass in orbit is worth 10-15 times equivalent Mass on the ground.
- If launch cost is $15,000 per Kilogram, then every kilogram in orbit is as valuable as 17 kilograms of Silver, a kilogram of Osmium or Iridium, 1/3 a kilogram of Gold or 1/5 of a kilogram of Platinum.
- From the perspective of being in space, a metric ton of water in space has a value of $15 Million Dollars. …….A one-kilometer-diameter C-type asteroid or dormant comet composed of 30 percent water, contains 150 million metric tons of water. If this had to be launched from Earth's surface it would cost 2,250 trillion dollars, which is obviously impractical.
- Mundane materials in space are as valuable as REE and Platinum Group Metals on the ground.

Estimated Value of a Typical 1 Kilometer Diameter M Class Asteroid	
Element	Value if sold at today's market price
Semiconductors	
Phosphorous (P)	1.24E+08
Gallium (Ga)	4.98E+10
Germanium (Ge)	3.45E+11
Arsenic (As)	1.29E+07
Selenium (Se)	3.15E+09
Indium (In)	3.97E+08
Antimony (Sb)	4.11E+05
Tellurium (Te)	1.13E+08
Platinum and Precious Metals	
Ruthenium (Ru)	1.46E+11
Rhodium (Rh)	6.61E+11
Palladium (Pd)	5.52E+10
Silver (Ag)	7.59E+08
Rhenium (Re)	1.98E+10
Osmium (Os)	2.25E+11
Iridium (Ir)	1.13E+12
Platinum (Pt)	3.33E+12
Gold (Au)	3.89E+10
Other Important Metals	
Copper (Cu)	1.60E+09
Cobalt (Co)	1.71E+11
Titanium (Ti)	1.35E+09
Chromium (Cr)	8.64E+09
Nickel (Ni)	1.55E+10
Molybdenum (Mo)	4.32E+05
Total	**6.20E+12**
Value	**$6.2 trillion**



Near-Earth Objects:

Generally between the orbits of Venus and Mars, with Apollo (60%) and Aten (6-8%) Asteroids crossing Earth's orbit and Amor (30%) Asteroids outside Earth's orbit and may cross Mars' orbit. Inner-Earth Objects are within Earth's orbit and may cross Venus' orbit. Dormant Comets may comprise 1-6 % of total number.

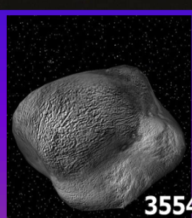
C-Type

75% of known asteroids
CI and CM chondrites:
volatiles: 5-20% water

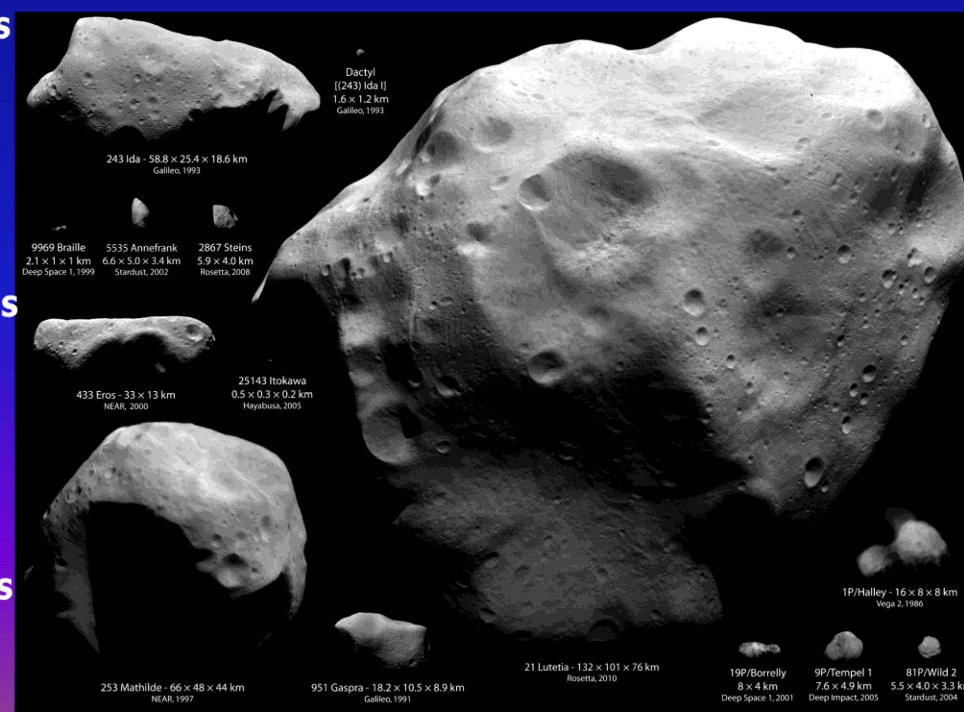
S-Type

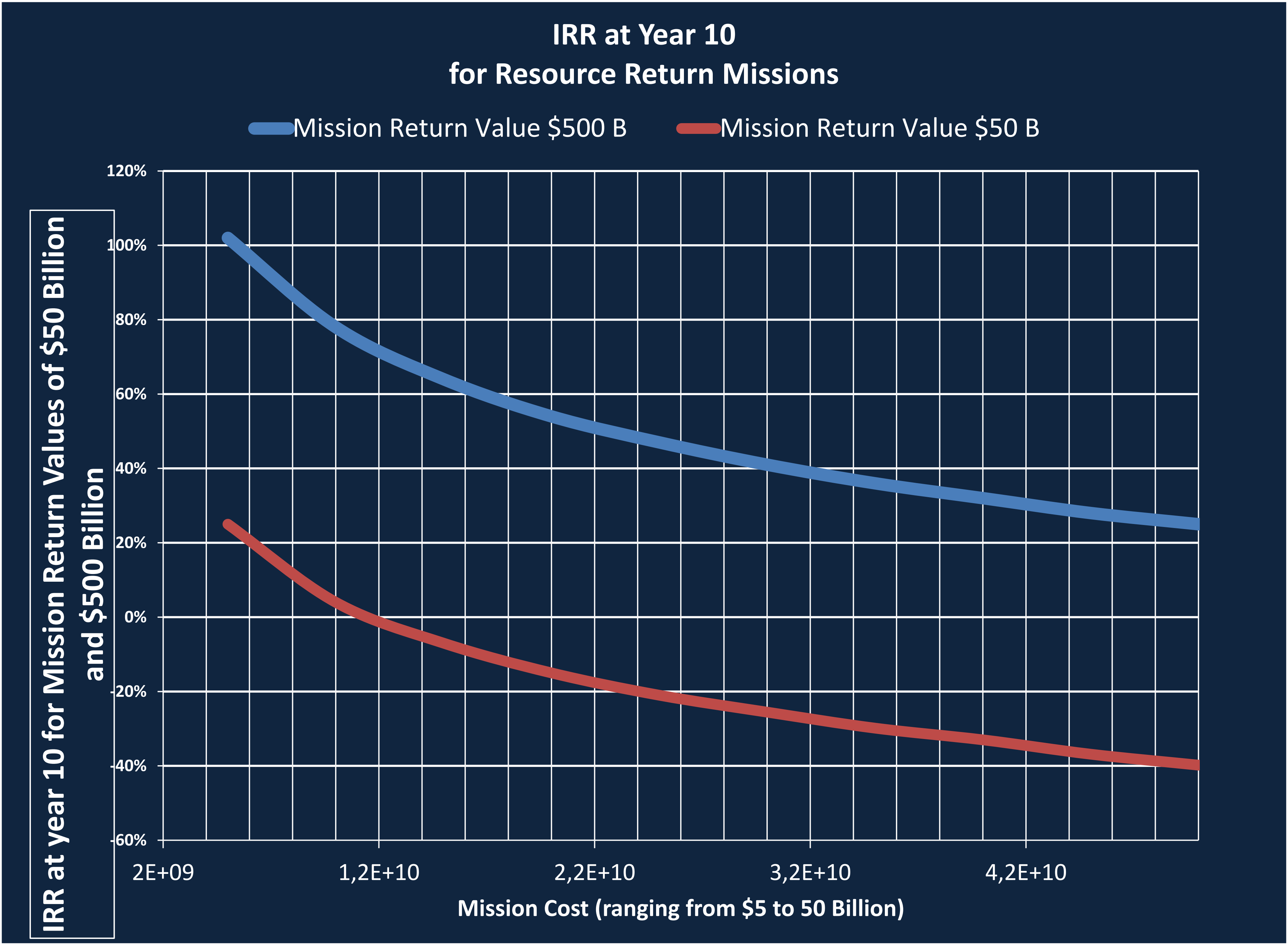
15% of known asteroids
dominant in inner belt:
olivine, pyroxene, Fe

M-Type

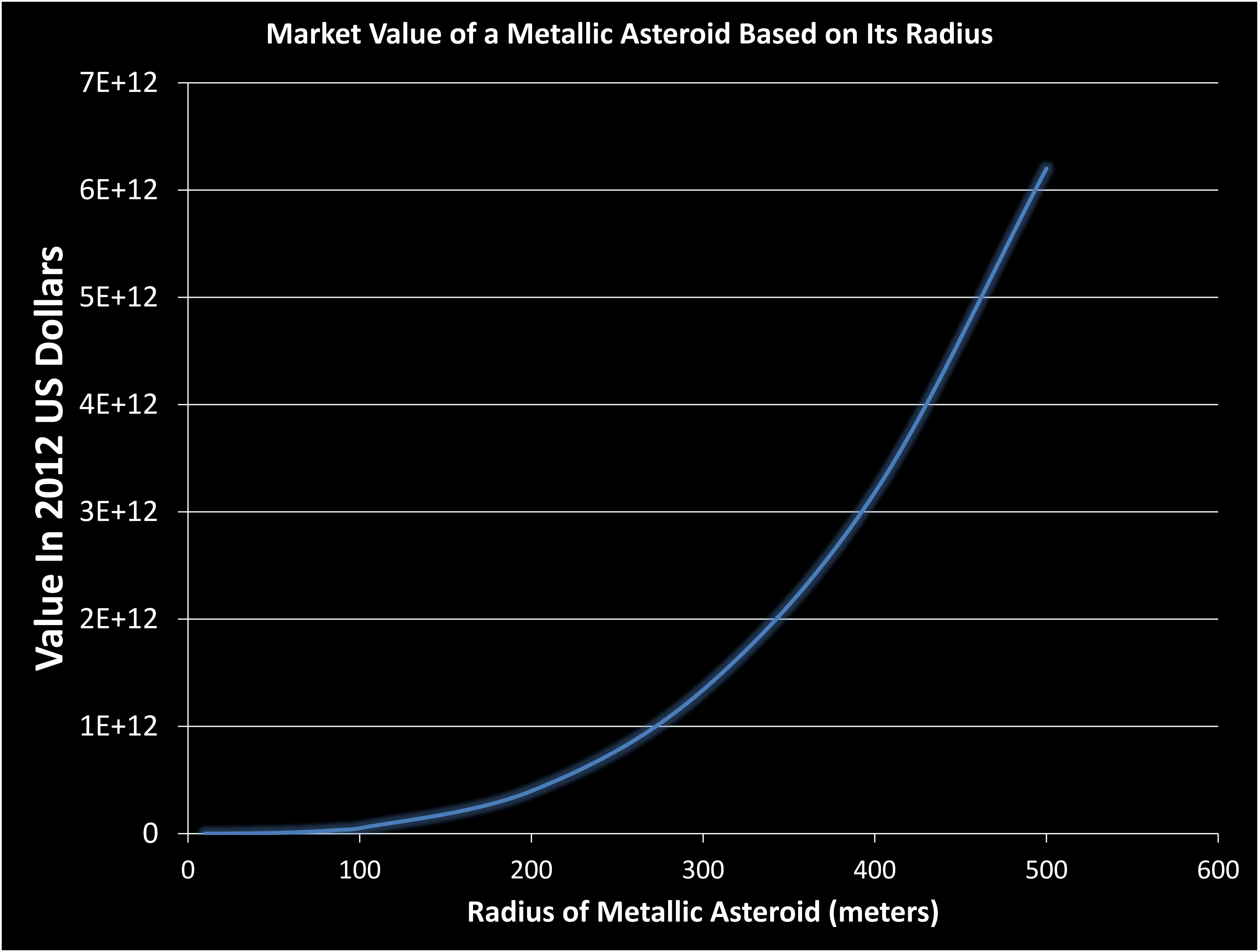


10% of known asteroids
Fe, Ni, Co, Pt-group

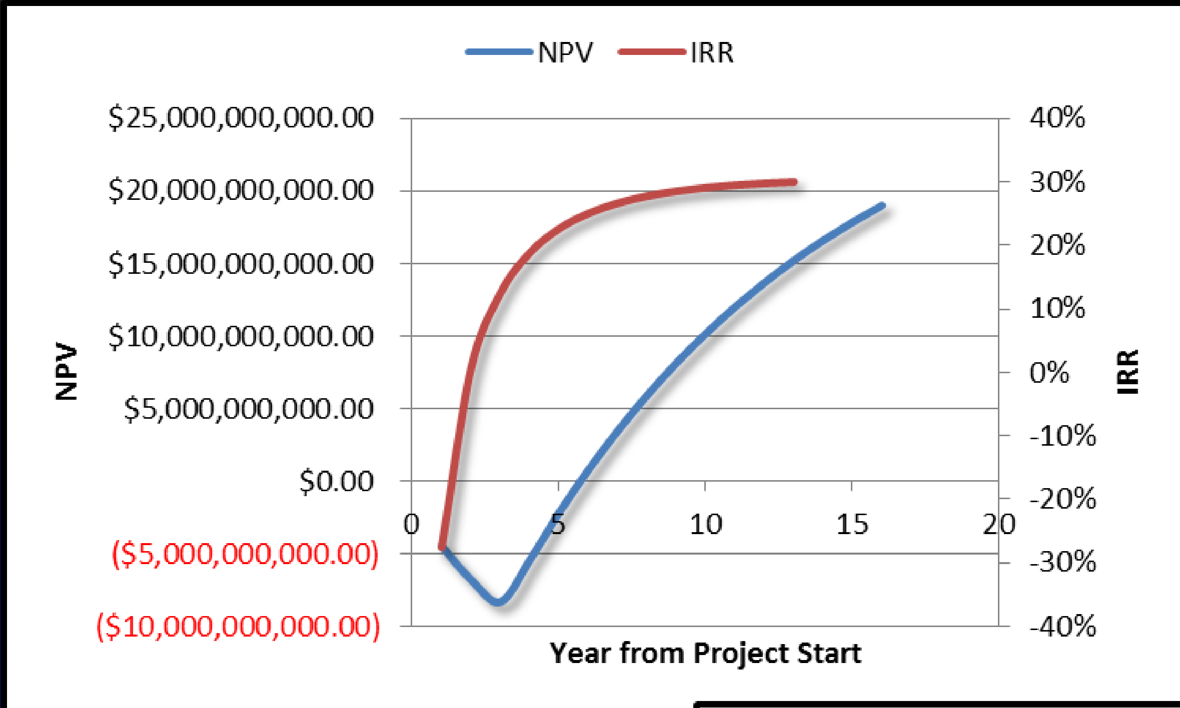




IRR at Year 10
for Resource Return Missions
Mission Return Value $500 B
Mission Return Value $50 B
120%
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
2E+09
1,2E+10
2,2E+10
3,2E+10
4,2E+10
Mission Cost (ranging from $5 to 50 Billion)
IRR at year 10 for Mission Return Values of $50 Billion and $500 Billion

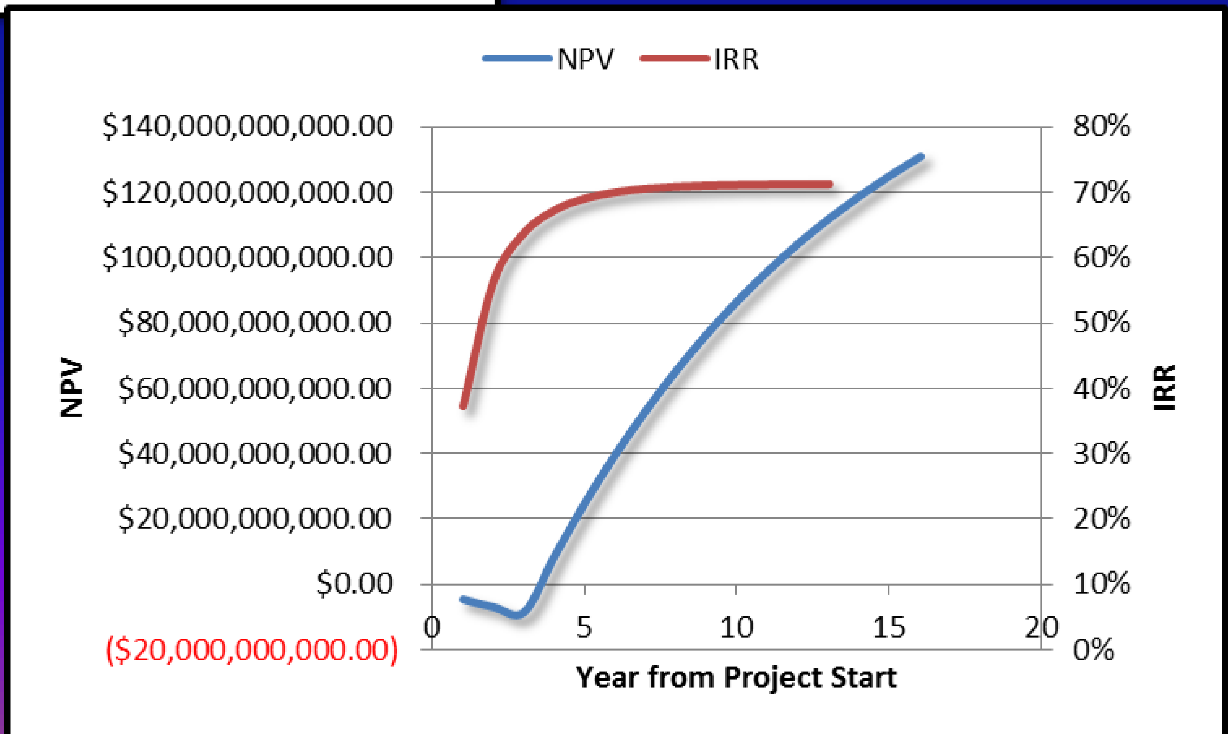


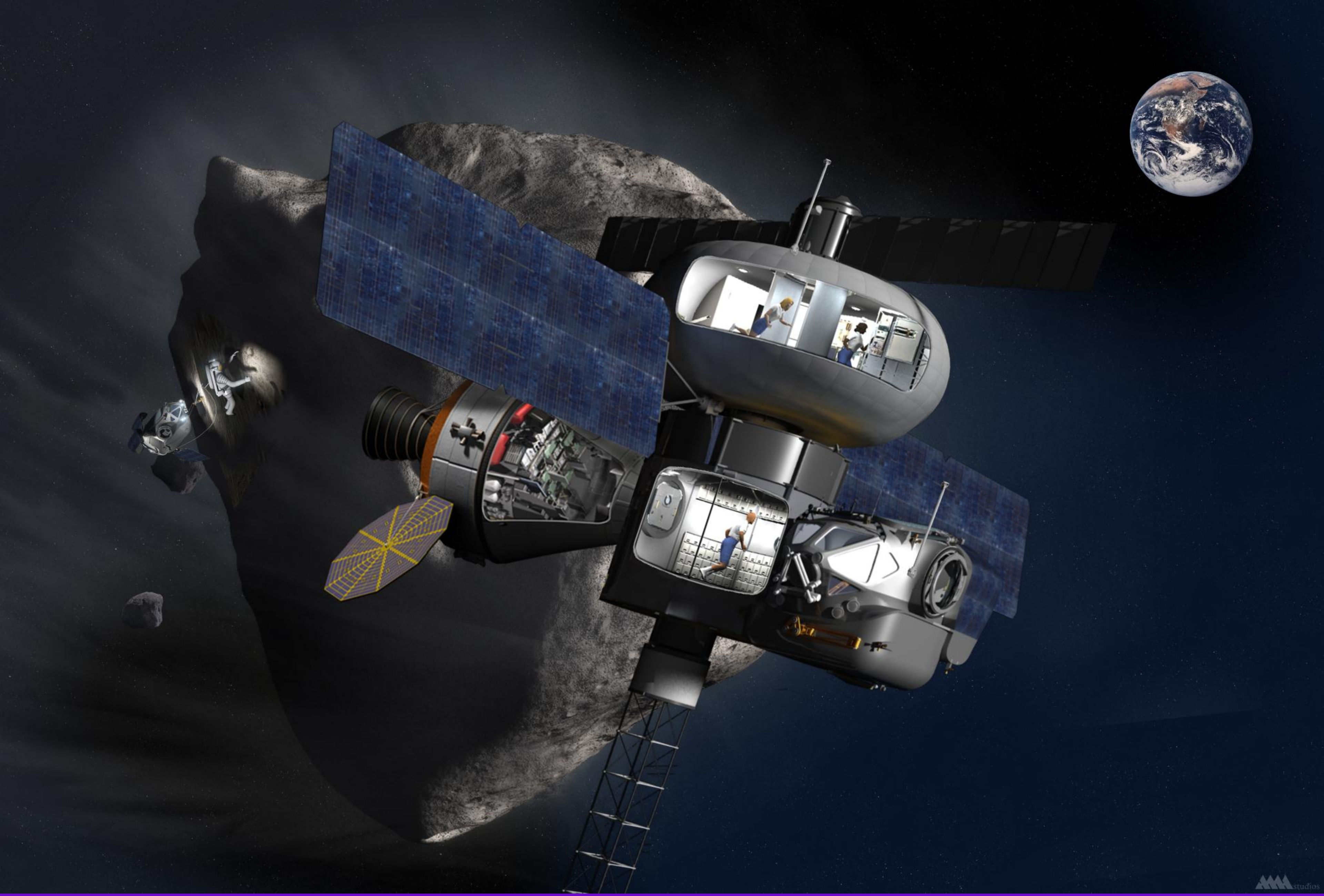
Market Value of a Metallic Asteroid Based on Its Radius
7E+12
6E+12
5E+12
4E+12
3E+12
2E+12
1E+12
0
Value In 2012 US Dollars
0
100
200
300
400
500
600
Radius of Metallic Asteroid (meters)



Left: Asteroid Return Mission with returns starting at year 9, continuing through year 20 with a total value of $100 Billion. Mission Cost $15.01 Billion

Right: Asteroid Return Mission with returns starting at year 9, continuing through year 20 with a total value of $500 Billion.





Significant attention has been directed toward mining the asteroids recently, but we have known of their value for more than 75 years

Last year, the estimated value of mineral production in the U.S. was $74.3 billion, a slight decrease from $75.8 billion in 2012. According to the U.S. Geological Survey's annual Mineral Commodity Summaries 2014 report, the 2013 decrease follows three consecutive years of increases. Net U.S. exports of mineral raw materials and old scrap contributed an additional $15.8 billion to the U.S. economy.

"To put this in context, the $90.1 billion value of combined mined, exported, and recycled raw materials is **more than five times greater than the 2013 combined net revenues of Internet titans: Amazon, Facebook, Google, and Yahoo.**

This illustrates the fundamental importance of mineral resources to the nation's economy, technology, and national security," said Larry Meinert, USGS Mineral Resources Program Coordinator.

The SPST (Space Propulsion Synergy Team) has taken the position that the ultimate reason for man’s establishing habitation and industrialization in low-Earth orbit and beyond is to provide improved quality of life on Earth and eventually for the continued evolution and survival of mankind.

(Henderson, E.M., Knuth, B., Rhodes, R.E., and Robinson, J. July 14-17, 2013 San Jose, CA, [49'" *AIAN ASMEISAEI ASEE Joint Propulsion Conference])*