Keck INSTITUTE FOR SPACE STUDIES
CALIFORNIA INSTITUTE OF TECHNOLOGY
JET PROPULSION LABORATORY

Three Dimensional (3D) Additive Construction for Space using In-Situ Resources - Shortcourse

Space Environment & Planetary Civil Engineering Basics

Pasadena, California

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SWAMP WORKS
NASA KENNEDY SPACE CENTER

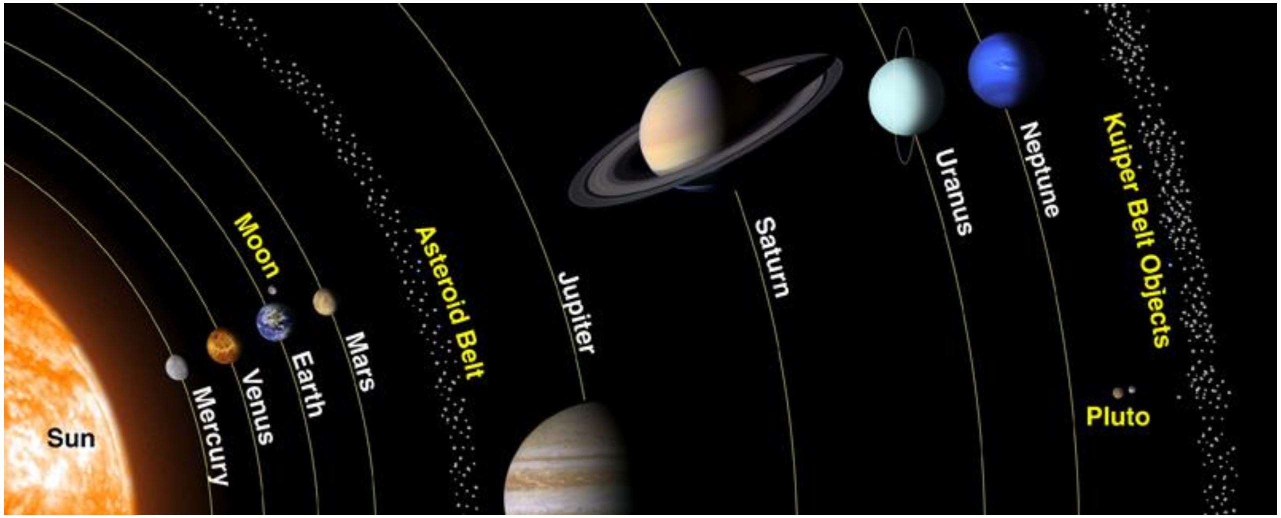
Space Environment - Objectives

- To grasp an *overview of the solar system bodies* and their variety
- To understand the key ways that *extreme environments* differ on other bodies compared to the Earth so that hardware and processes may be designed appropriately
- To understand especially the environments of the *Moon, asteroids, and Mars* for 3D Additive Construction for Space using In-Situ Resources

Space Environment: Topic Outline

- Overview of the Solar System
- Environmental Considerations
- The Moon
- Asteroids
- Mars

Overview of the Solar System



http://spaceplace.nasa.gov

- Zones from Planet Formation:
  - Terrestrial Planets – materials accreting close to sun
  - Main Asteroid Belt

The "Frost Line"

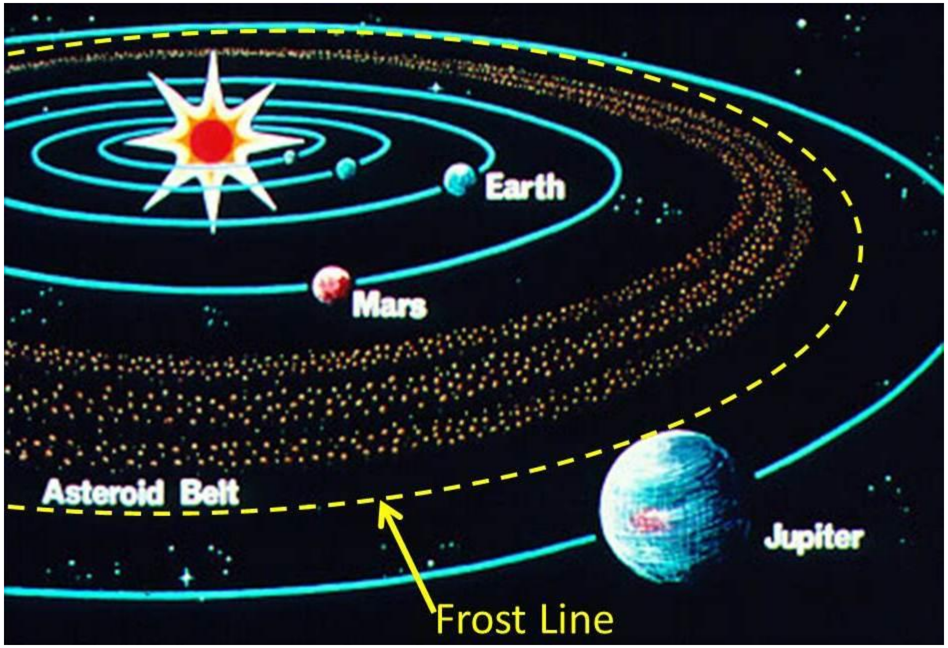
  - Gas Giants– volatiles that could accrete farther from the sun
  - Moons of Gas Giants – icy bodies, some capture KBO's
  - Kuiper Belt Objects (KBO's) – icy bodies
  - Oort Cloud – icy bodies, the origin of comets

Terrestrial Planets Summary

- Lots of silicates
- Liquid water (H_2O) abundant on earth
- Water ice exists in special reservoirs elsewhere
  - Polar craters of Mercury and the Moon
  - Under the surface of Mars and at its poles
  - Comets and possibly asteroids
- Ore body formation maybe not as prevalent on other planets compared to Earth due to lack of liquid water, plate tectonics
  - But little is known of subsurface geology on these worlds
- Atmospheric density and rotation periods vary wildly due to chaotic history

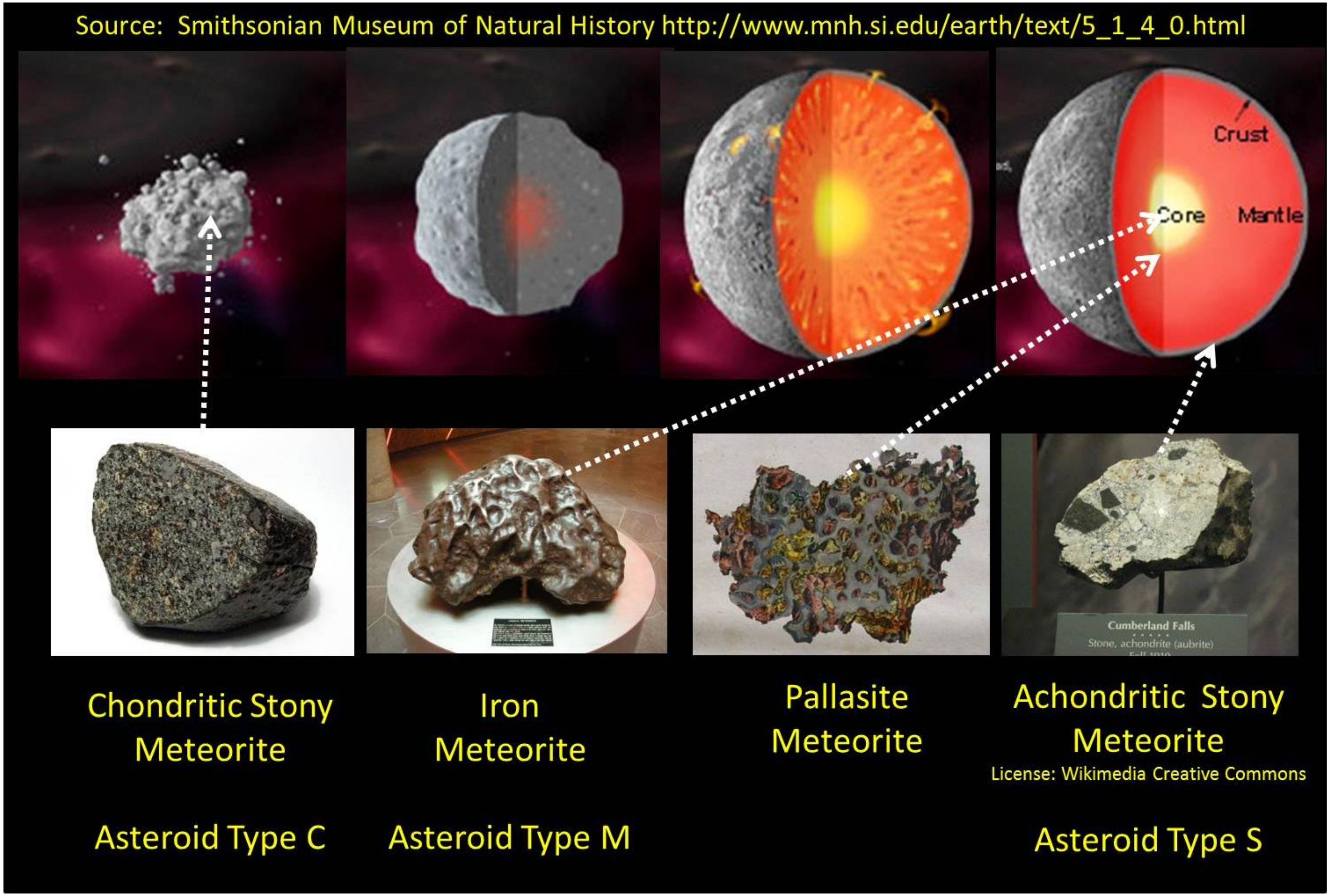
Asteroid Belt and Frost Line

- Asteroids are leftover material that failed to form a planet because of the stirring effect of Jupiter
- Near Earth Asteroids were Main Belt asteroids that got kicked into the inner solar system by resonances with larger planets
- They survive millions of years before crashing into a terrestrial planet



http://pixgood.com

Larger Asteroids Differentiated



What are Space Resources?

- **Resources**
  - Traditional**:** **Water**, atmospheric gases, volatiles, solar wind volatiles, metals, etc.
  - Non-traditional: Trash and wastes from crew, spent landers and residuals, etc.
- **Energy**
  - Permanent/Near-Permanent Sunlight
    - Stable thermal control & power/energy generation and storage
  - Permanent/Near-Permanent Darkness
    - Thermal cold sink for cryo fluid storage & scientific instruments
- **Environment**
  - Vacuum
  - Micro/Reduced Gravity
  - High Thermal Gradients
- **Location**
  - Stable Locations/'Real Estate':
    - Earth viewing, sun viewing, space viewing, staging locations
  - Isolation from Earth
    - Electromagnetic noise, hazardous testing & development activities (nuclear, biological, etc.), extraterrestrial sample curation & analysis, storage of vital information, etc.

Gerald. B Sanders/JSC, gerald.b.sanders@nasa.gov

Environmental Considerations

- Gravity
- Atmosphere or Vacuum
- Dust
- Rotation Period (day/night cycles)
- Seasons
- Temperature Extremes
- Particle Radiation
- Electrostatics and charging
- Solar Flux
- Magnetic Field
- Soil Characteristics
- Ice Characteristics
- Subsurface Geology
- Planetary Protection

Moon, Mars, & Near Earth Objects (NEOs)

	Moon	Mars	NEO
Gravity	1/6 g	3/8 g	Micro-g
Temperature (Max) (Min.) (Min. Shade)	110 °C/230 °F -170 °C/-274 °F -233 °C/-387.4 °F	20 °C/68 °F -140 °C/-220 °F	110 °C/230 °F -170 °C/-274 °F -233 °C/-387.4 °F
Solar Flux	1352 W/m^2	590 W/m^2	Varied based on distance from Sun
Day/Night Cycle	28+ Days	24.66 hrs	Varied - hrs
Surface Pressure	$1x10^{-12}$ torr	7.5 torr	$1x10^{-12}$ torr
Atmosphere	No	Yes CO_2, N_2, Ar, O_2	No
Soil	Granular	Granular & clay; low hydration to ice	Varied based on NEO type

NEO's have aspects of both the Moon and Mars

It is the NEO micro-gravity environment that is the largest difference between destinations

Gravity

Body	Gravity (m/s2)	Gravity (g)
Mercury	3.7	0.38
Venus	8.78	0.904
Earth	9.8	1.000
Earth's Moon	1.622	0.1654
Mars	3.711	0.376
Phobos (Martian moon)	0.0057	0.00058
Deimos (Martian moon)	0.003	0.0003
Ceres (Main belt asteroid, dwarf planet)	0.28	0.029
Vesta (Main belt asteroid, protoplanet)	0.25	0.025
25143 Itokawa (Near Earth asteroid)	~0.0001	~0.00001
Bennu (Near Earth asteroid)	~0.00001	~0.000001
Europa (A moon of Jupiter)	1.314	0.134

Effects of Low Gravity

- Low traction for reaction force to mining
- Liquid slosh is amplified
- Kicking up dust is amplified
- Dynamics like walking are in slow motion (fall time to ground between steps is longer)
- Beware: rotational inertia is not reduced, but gravity to resist tipping is reduced!

Atmosphere and Weather

- Atmosphere tends to mediate the temperature swings between day and night
- In vacuum, cold welding may occur
- Near Vacuum: Mercury, the Moon, moons of Mars, near Earth asteroids
- Some have very little atmosphere, like Europa
- Thin atmosphere: Mars
- Dense atmosphere: Earth
- Very dense atmosphere: Venus
- Mars has hurricanes, diurnal (daily) wind patterns, dust storms, dust devils, seasons

Dust

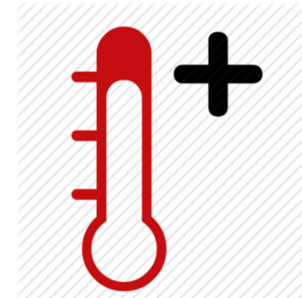
http://www.astrobio.net/albums/lunarmoon/acn.sized.jpg

- Kicked up by rovers, digging and boots
- Transported by the wind on Mars
- Suspected electrostatic transport on the Moon, but not a large flux
- Coats surfaces and is very difficult to remove
  - Radiators, solar panels, windows, optics
- Gets suspended in gas flows and difficult to filter out
  - Clogs filters, damages pumps, can damage human lungs

Rotation Periods, Seasons

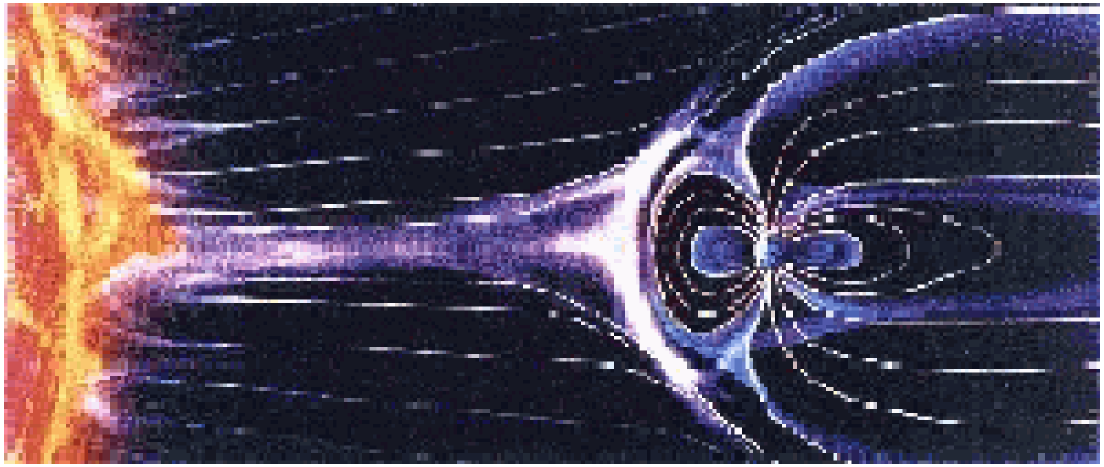
- Mercury and Venus turn very slowly due to tidal forces with the sun
- The Moon is tidally locked to face the Earth, hence has a 29.5 day day/night cycle
- Mars rotation 24 hr 37 min
- Mars year is 1.88 Earth years
  - Atmospheric pressure varies 30%
  - Polar caps grow and shrink with CO_2 ice forming

Temperatures

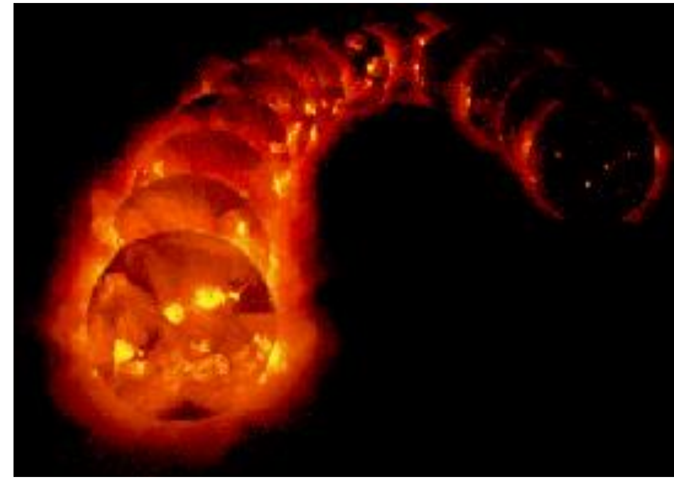


Body	Min Temp (Celsius)	Max Temp (Celsius)
Mercury at equator	+100	+700
Venus	+465	+465
Earth	-88	+58
Moon at equator	-173	+117
Moon in polar crater	~-240 (40 K)	~-240 (40 K)
Mars	-125	+20
Ceres	~-105	~-38
Europa	~-223	~-148

Space Radiation = High-speed Atomic Particles and Electromagnetic Waves



http://srag-nt.jsc.nasa.gov/spaceradiation/what/what.cfm



Lockheed Martin Solar & Astro Physics Lab

- On Earth, the magnetic field and the thick atmosphere block out most particle radiation before it reaches the surface
- Planetary Bodies without these features have high radiation at the surface (e.g. Moon, Mars, Asteroids)
- Galactic Cosmic Radiation (GCR) is worse in the outer solar system and is omni-directional and omni-present
- Solar Particle Events (SPE) flares are worse in the inner solar system and are directional / detectable coming from the Sun

Electrostatics, Magnetics, Solar Flux

- In vacuum, electrostatic charging may be worse
- Ultra Violet light may charge surfaces via the photoelectric effects
- Planets may have some local remnant magnetic field, but in the inner solar system, only Earth has a global magnetic field
- Solar flux (for solar energy) at Mars is about 44% of Earth's due to farther distance from the sun

Unique Geological History

- Soil particle sizes and roughness
- Soil compaction and porosity
- Layering in the soil
- Depth to bedrock
- Ice in the subsurface, composition and quantity
- Terrain and subsurface features
- Ore bodies?

Planetary Protection

- Committee on Space Research (COSPAR)
  - Cat. I: no planetary protection (e.g, Mercury)
  - Cat. II: remote chance of compromise (e.g., Moon)
  - Cat. III: Flyby or orbiter missions with significant chance of compromise (e.g., Mars orbiter)
  - Cat. IV: Lander missions to the same places as III
    - Cat IV(c): lander that touches a special location such as Martian ice
  - Cat V deals with back-contamination of Earth

The Moon

- Gravity ~1/6 of Earth
- Hard vacuum (1x 10^{-12} torr)
- Large temperature swings (especially at Equator)
- Long night (~14 Earth-days)
- Very dusty
- Sharp, angular soil with high glass content
  - Very abrasive, electrostatically charged, 100 micron and less
- Soil very compacted below top 2-3 cm layer
  - But we don't know about compaction in the polar craters
- Unprotected from space particle radiation
- Solar flux same as at Earth
- Heating comes almost entirely from the Sun (at night the lunar surface is warmed slightly by Earth).

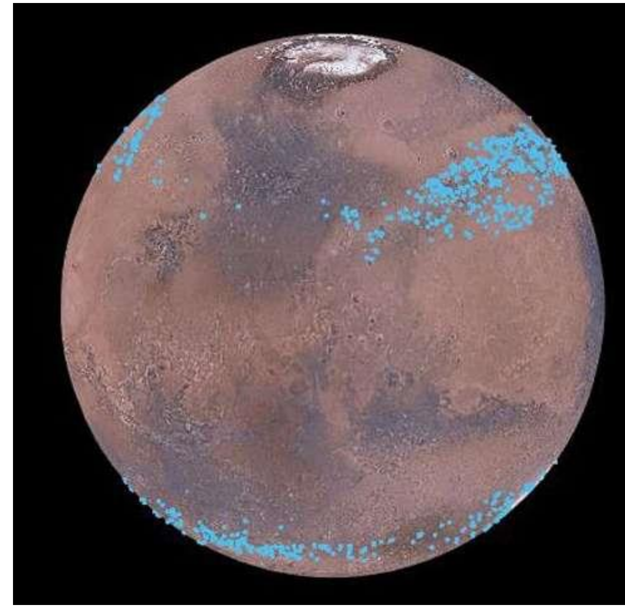
Near Earth Asteroids

- Gravity is negligible (~1/1000th G)
- Hard vacuum (1x 10^{-12} torr)
- May be "rubble piles"
- Might have regolith on the surface & dust ponds
- Regolith may be denuded of fine particles at the surface; appear to be gravelly with boulders
- Many Different types of asteroids
- Unprotected from particle radiation
- Solar flux about the same as at Earth

Mars

- Gravity ~3/8 of Earth (0.376 G)
- Atmospheric pressure ~1% of Earth's, but varies seasonally by 30% as it freezes and unfreezes from the polar caps
- Wind only has ~10 % dynamic force of equivalent Earth's wind
- Mars has CO_2 frost & snow
- Sand carried by the wind still abrades like on Earth
- Atmosphere mostly carbon dioxide (95.5 %)
- Very dusty atmosphere; dust storms, dust devils
- Four seasons – seasons are twice as long as on Earth
- Mars gets about 40 percent more energy from the sun during perihelion — when the planet is closest to the sun — than during aphelion
- In the winter, much like on Earth, heavy storms of thick cloud cover and dust move over Mars' continents toward the equator.
- When Mars sweeps closest to the sun during its southern hemisphere summer, temperatures increase greatly; the extra energy is enough to launch dust storms that envelop large regions of Mars — sometimes the entire planet — for weeks or months.
- Global dust storms tend to occur only during perihelion season and once every three or so Martian years

Mars, continued



Credit: Mars Digital Image Model, NASA/Nanna Karlsson

- Radiation environment on the surface is bad
- Soil is weathered, behaves like terrestrial soil
- Soil is diverse
- Geology is complex
- Little is known about subsurface geology
- Mars is in glacial retreat – radar obseravtions
- The glaciers are located in belts around Mars between the latitudes 30.0-50.0, equivalent to just south of Denmark's location on Earth.
- The glaciers are found on both the northern and southern hemispheres.
- Mixture of CO_2 and water ice and clathrates

(A clathrate is a snow like substance that can exist below 283K (10 °C) at a range of pressures of carbon dioxide)

  - Varying mechanical strength
  - Ice is on the surface at high latitudes
  - Ice is near the surface at moderate latitudes
  - Ice is deep beneath the surface at low latitudes

Space Environment Summary

- Bodies in space have vastly different environments than Earth
- To work on another solar system body, equipment and methods must be adapted to that body's environment
- Must consider gravity, atmosphere, thermal, radiation, dust, & many other characteristics
- We have an exciting time ahead of us, because there are many <u>resource rich destinations</u> in space

Lunar and Mars Resources

Moon Resources

Ilmenite - 15%
- $FeO \bullet TiO_2$ (98.5%)

Pyroxene - 50%
- $CaO \bullet SiO_2$ (36.7%)
- $MgO \bullet SiO_2$ (29.2%)
- $FeO \bullet SiO_2$ (17.6%)
- $Al_2O_3 \bullet SiO_2$ (9.6%)
- $TiO_2 \bullet SiO_2$ (6.9%)

Olivine - 15%
- $2MgO \bullet SiO_2$ (56.6%)
- $2FeO \bullet SiO_2$ (42.7%)

Anorthite - 20%
- $CaO \bullet Al_2O_3 \bullet SiO_2$ (97.7%)

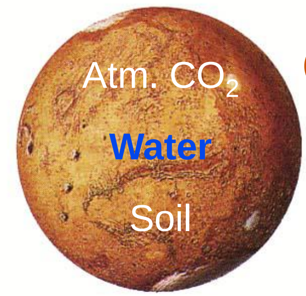
Water (?, >1000 ppm)

Solar Wind
- Hydrogen (50 - 100 ppm)
- Carbon (100 - 150 ppm)
- Nitrogen (50 - 100 ppm)
- Helium (3 - 50 ppm)
- ^{3}He (4 - 20 ppb)

Mars Resources

Regolith*
- Silicon Dioxide (43.5%)
- Iron Oxide (18.2%)
- Sulfur Trioxide (7.3%)
- Aluminum Oxide (7.3%)
- Magnesium Oxide (6.0%)
- Calcium Oxide (5.8%)
- Other (11.9%)
- Water (2 to >50%)[XX]

*Based on Viking Data
[XX]Mars Odyssey Data



Atmosphere
- Carbon Dioxide (95..5%)
- Nitrogen (2.7%)
- Argon (1.6%)
- Oxygen (0.1%)
- Water (210 ppm)

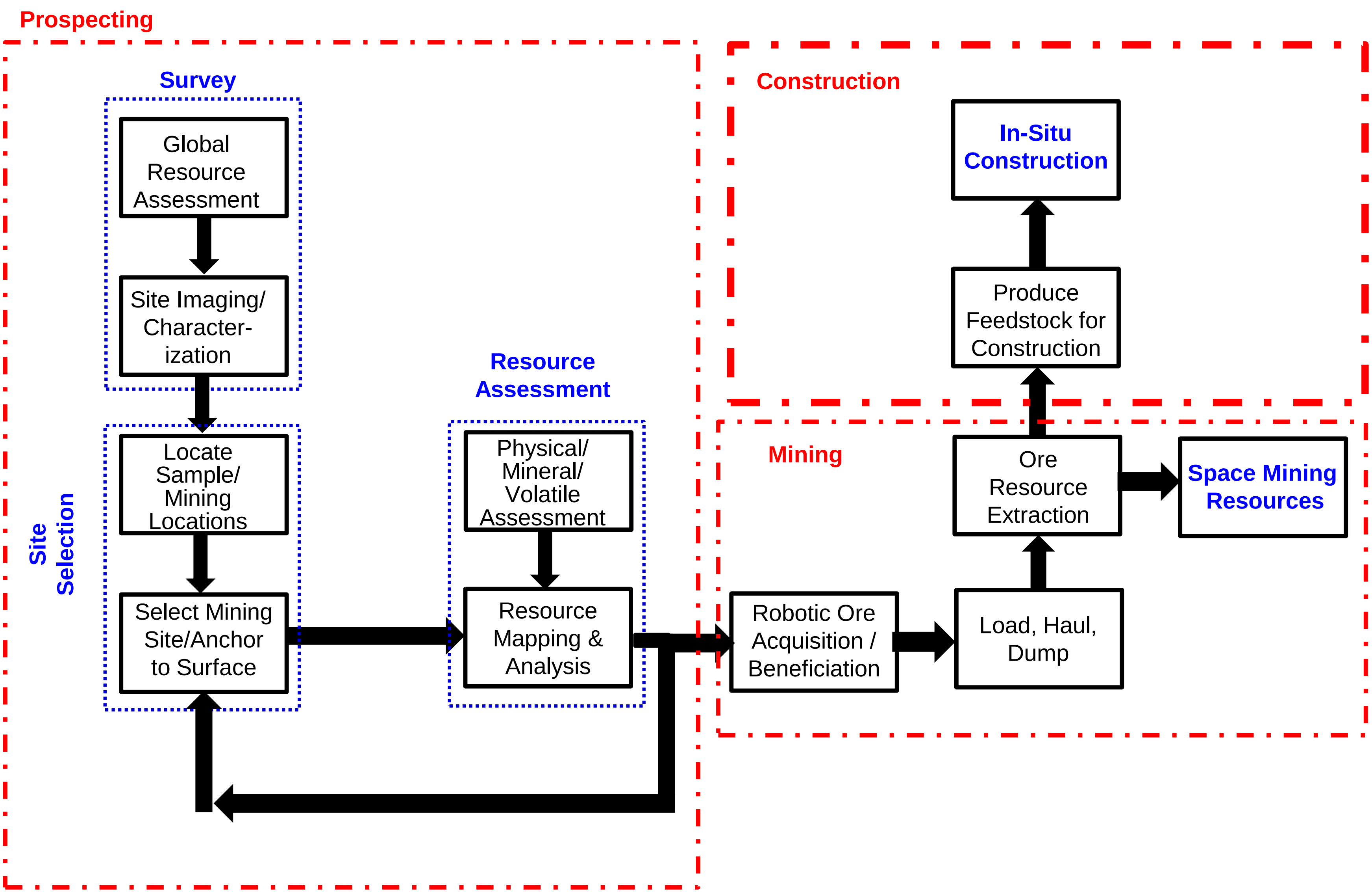
Lunar Resources

- Oxygen is the most abundant element on the Moon
- Solar wind deposited volatile elements are available at low concentrations
- Metals and silicon are abundant
- Water may be available at poles
- Lunar mineral resources are understood at a global level with Apollo samples for calibration

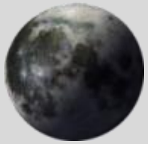
Mars Resources

- Atmospheric gases, and in particular carbon dioxide, are available everywhere at 6 to 10 torr (0.1 psi)
- Viking and Mars Odyssey data shows that water is wide spread but spatial *distribution and form of water/ice is not well understood* (hydrated clays and salts, permafrost, liquid aquifers, and/or dirty ice)

Space Mining/Construction Tasks



Credit: G. Sanders, NASA JSC



Space Resources

Four major resources on the Moon:

- **Regolith**: oxides and metals
  - Ilmenite 15%
  - Pyroxene 50%
  - Olivine 15%
  - Anorthite 20%
- Solar wind volatiles in regolith
  - Hydrogen 50 – 150 ppm
  - Helium 3 – 50 ppm
  - Carbon 100 – 150 ppm
- Water/ice and other volatiles in polar shadowed craters
  - 1-10% (LCROSS)
  - Thick ice (SAR)
- Discarded materials: Lander and crew trash and residuals

Three major resources on Mars:

- **Atmosphere**:
  - 95.5% Carbon dioxide,
  - 2.7% Nitrogen,
  - 1.6% Argon
- Water in soil: concentration dependant on location
  - 2% to dirty ice at poles
- Oxides and metals in the soil

Resources of Interest:

- **Oxygen**
- **Water**
- **Hydrogen**
- **Metals**
- **Silicon**
- **Gases**
- **Aggregates**
- **Binders**
- **Energy**

~85% of Meteorites are Chondrites

Ordinary Chondrites 87%

FeO:Si = 0.1 to 0.5

Fe:Si = 0.5 to 0.8

Pyroxene
Olivine
Plagioclase
Diopside
Metallic Fe-Ni alloy
Trioilite - FeS

Source metals (Carbonyl)

Carbonaceous Chondrites 8%

Highly oxidized w/ little or no free metal

Abundant volatiles: up to 20% bound water and 6% organic material

Source of water/volatiles

Enstatite Chondrites 5%

Highly reduced; silicates contain almost no FeO

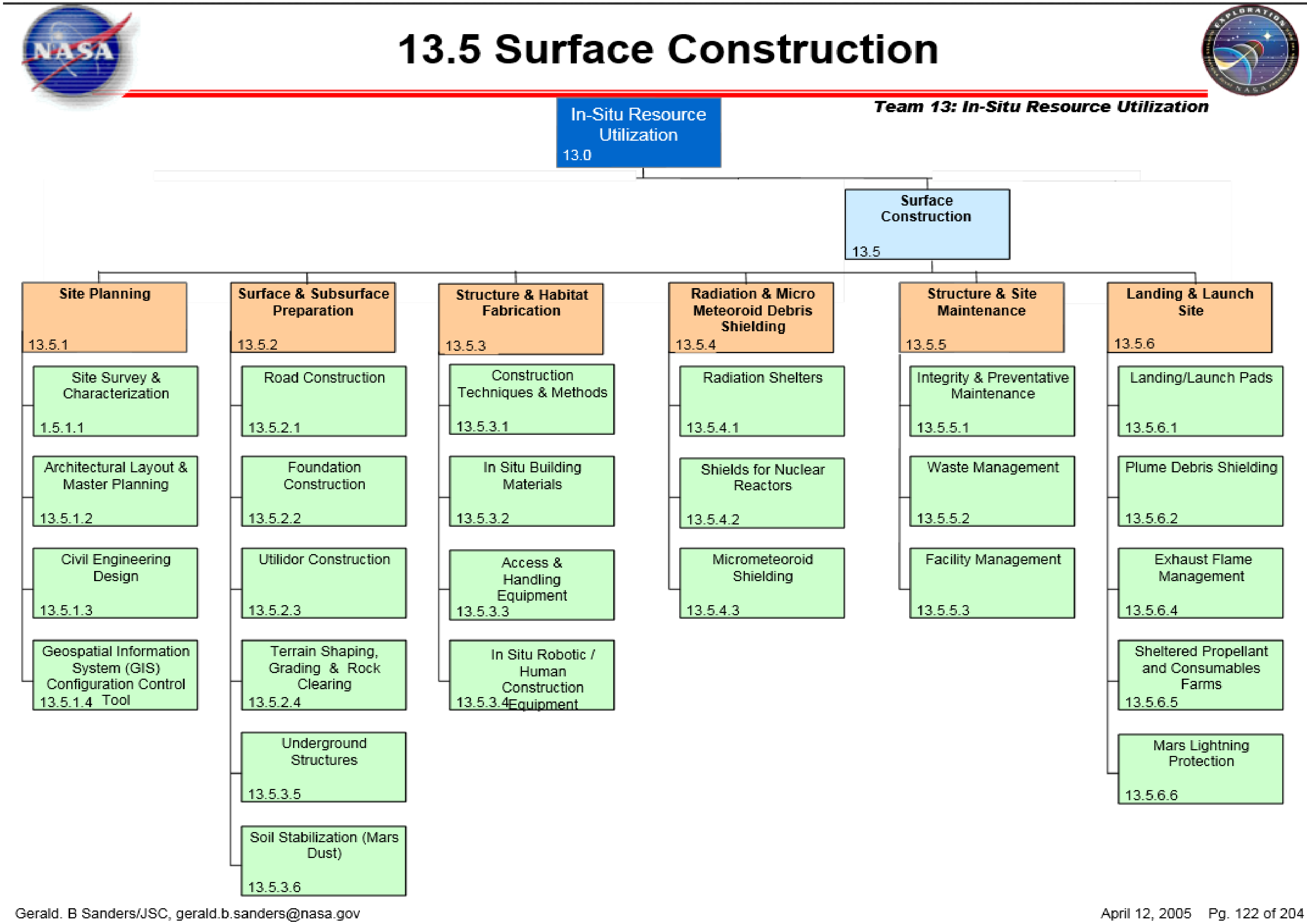
60 to 80% silicates; Enstatite & Na-rich plagioclase

20 to 25% Fe-Ni

Cr, Mn, and Ti are found as minor constituents

Easy source of oxygen (Carbothermal)

Surface Construction

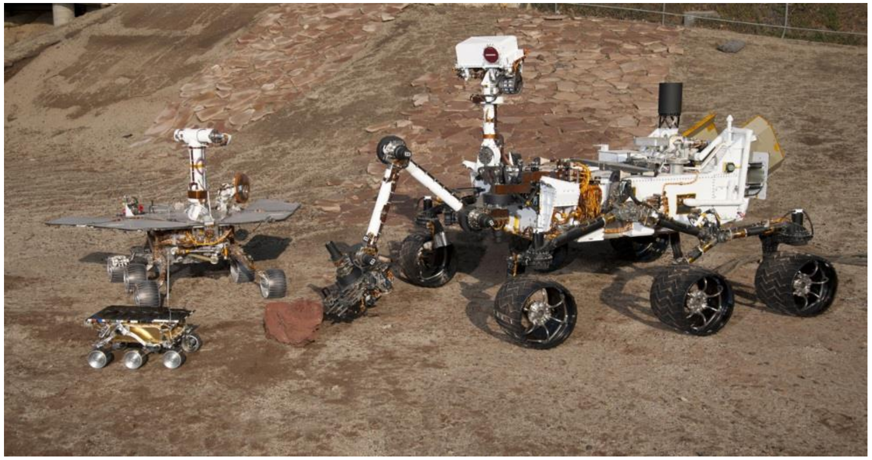


Resource Prospecting / Science Space Missions

NASA Lunar Resource Prospector -2018

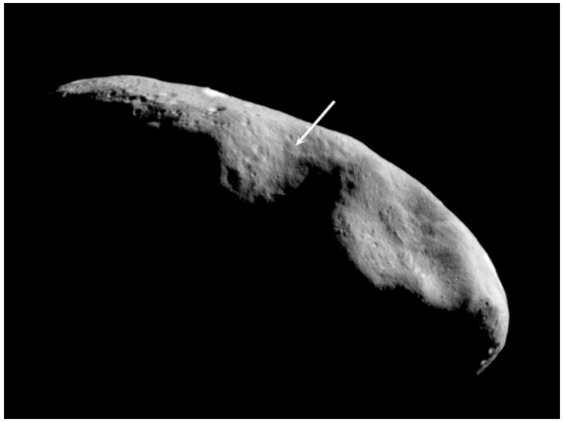
Jaxa Hayabusa I - 2005
Jaxa Hayabusa II - 2014

ESA Rosetta / Philae - 2014

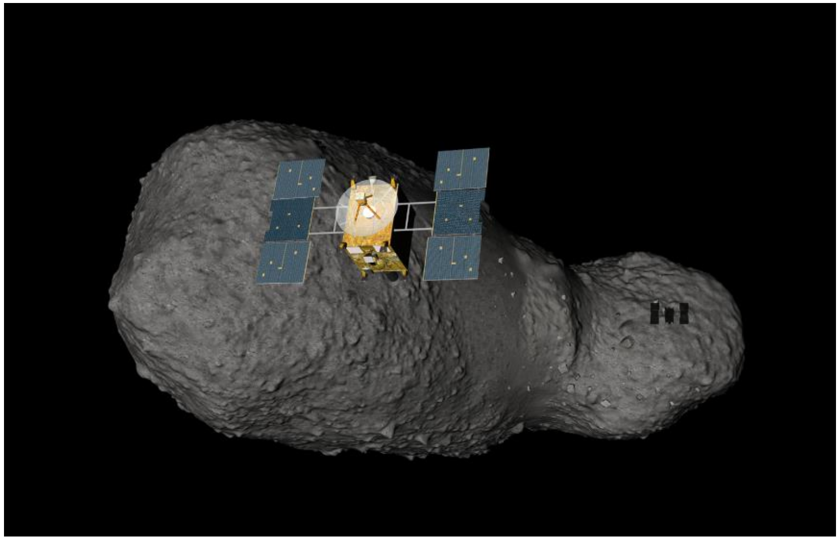


NASA Mars Science Lander - 2011

Asteroid Operations -



Eros Near Shoemaker Impact Site - 2001

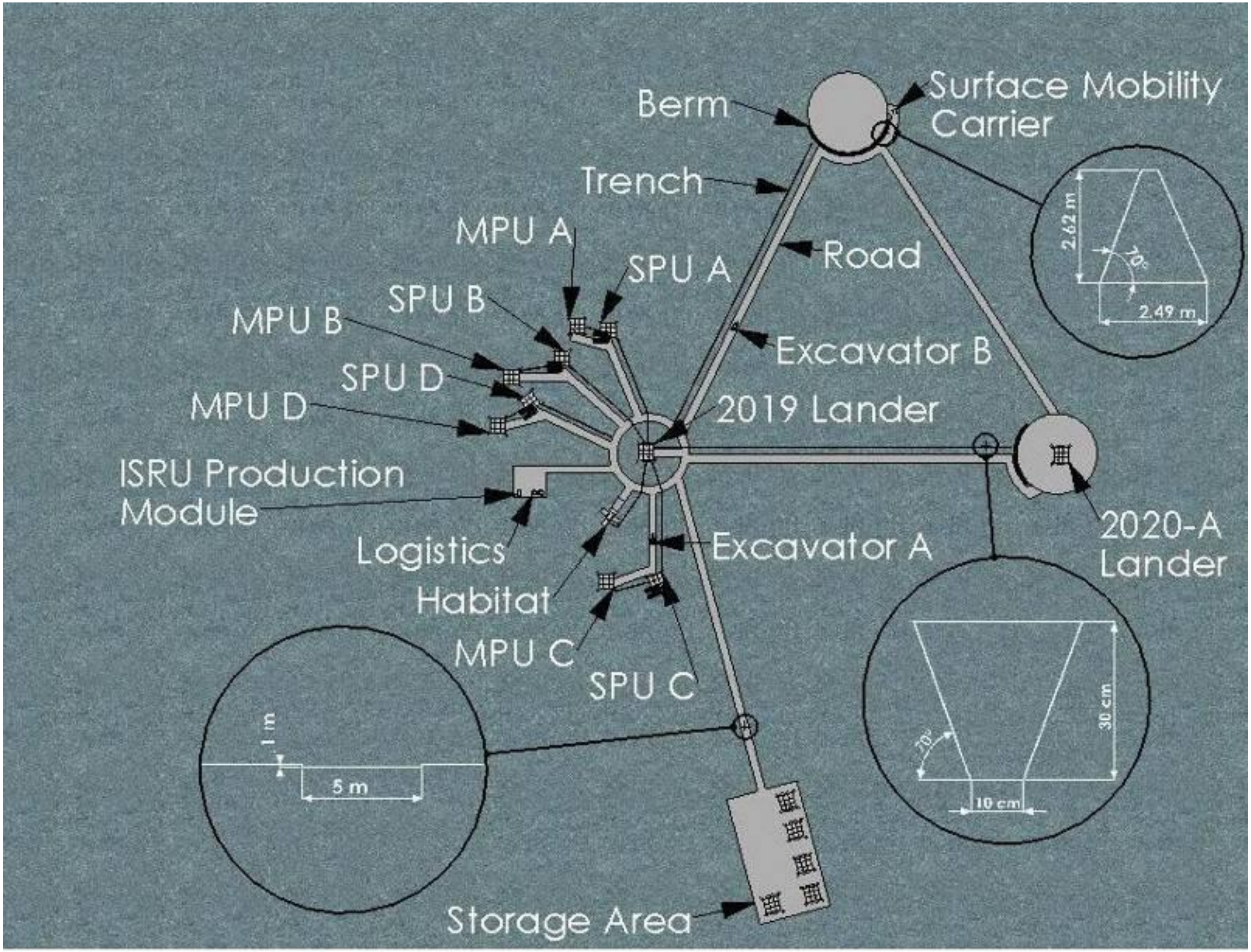


Hayabusa 1 at Itokawa - 2005

Near Earth Asteroid (NEA) Challenges:

Hard to detect with telescopes
Orbital mechanics – moving target
Deep space propulsion
Business Case
Defining ore prior to visitation
Space Mining International Law
1/1000 Gravity of Earth
Varying gravity field
Anchoring likely to be needed
Dusty Regolith Lofted
Tumbling dynamics
Communications Latency
Autonomy
In-Situ processing of Ore
Rubble Pile Internal Structure

Concept: Lunar Base Master Planning



Criteria for Lunar Outpost Excavation, R. P. Mueller and R. H. King, Space Resources Roundtable, 2007

Planetary Surface Construction Tasks

Launch/Landing Pads

Beacon/Navigation Aids

Lighting Systems

Communications Antenna Towers

Blast Protection Berms

Perimeter Pad Access & Utility Roads

Spacecraft Refueling Infrastructure

Power Systems

Radiation, Thermal & Micro Meteorite Shielding

Electrical Cable/ Utilities Trenches

Foundations / Leveling

Trenches for Habitat & Element Burial

Regolith Shielding on Roof over Trenches

Equipment Shelters

Maintenance Hangars

Dust free zones

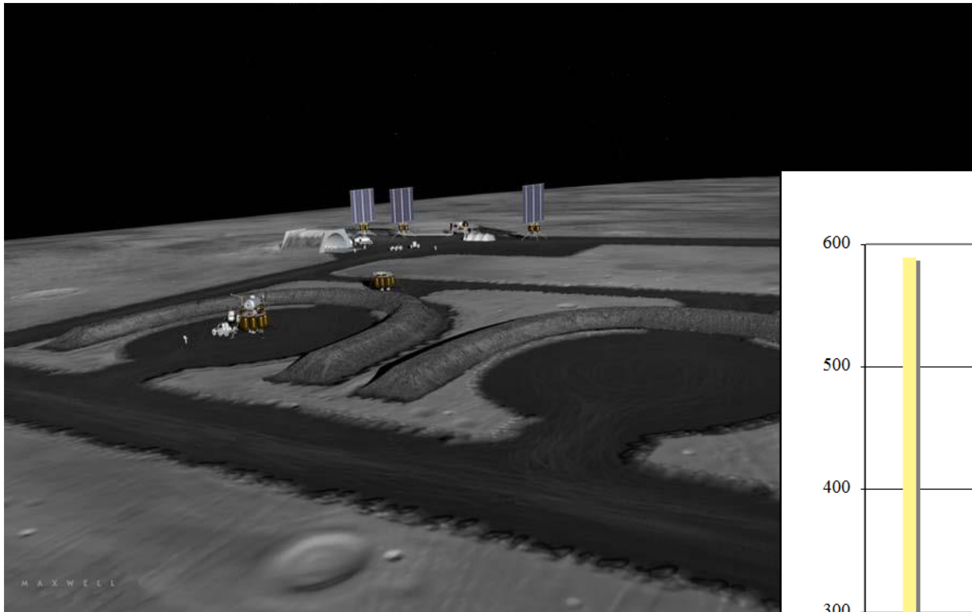
Thermal Wadi's for night time

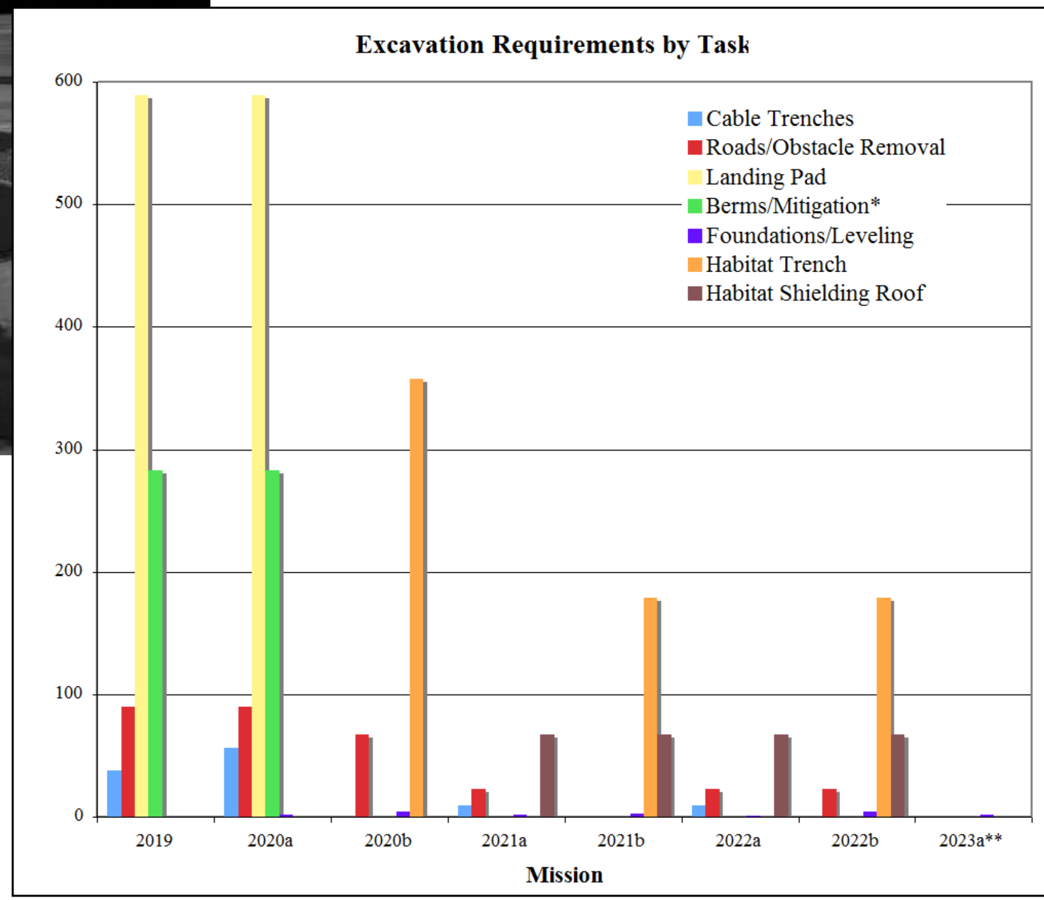
Regolith Mining for O2 Production

H2O Ice/Regolith Mining from Shadowed Craters

Lunar Surface Construction Tasks

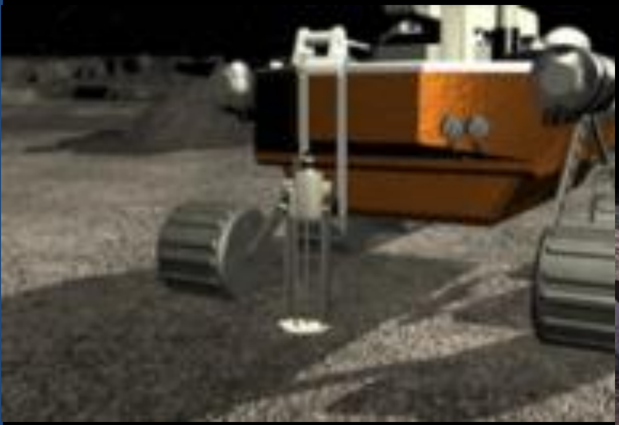
Criteria for Lunar Outpost Excavation
R. P. Mueller and R. H. King
Space Resources Roundtable –SRR IX
October 26, 2007
Golden, Colorado





SUMMARY	
Task	%
Trenching	4
Clearing and Compacting	48
Building Berms	18
Habitat Shielding	31
	100
Ice Mining	17
Regolith Mining	83
Construction	84
Mining	16

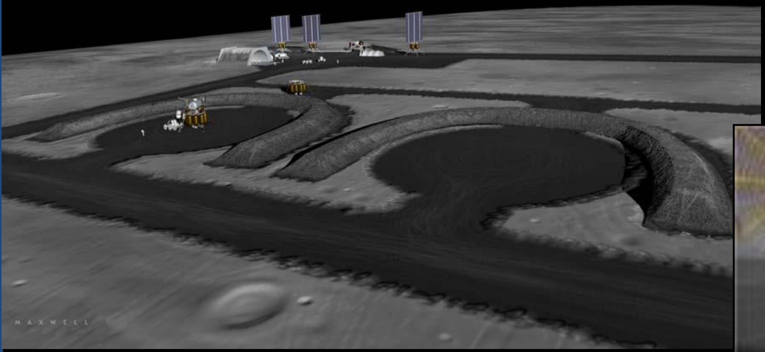
Lunar Mission Space Civil Engineering Capability Concepts



Resource Prospecting – Looking for Resources

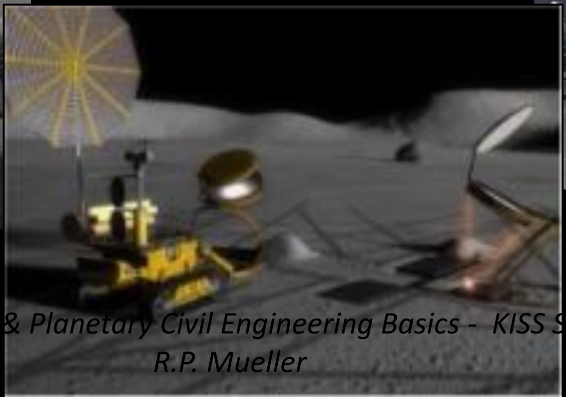
Excavation & Regolith Processing for O_2 Production, Binders & Aggregates

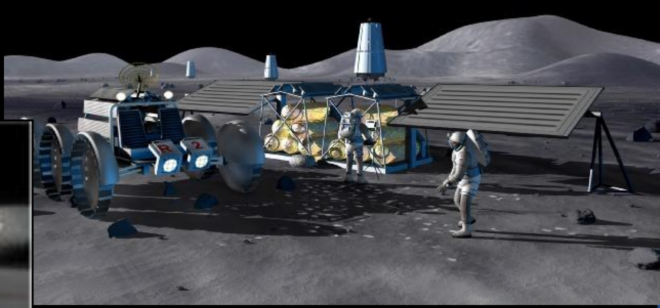
Propellant Processing with Lander & Pad Infrastructure



Habitat, Hangars, Dust Free Zones, Landing Pads, Berm, and Road Construction

Thermal Energy Storage Construction

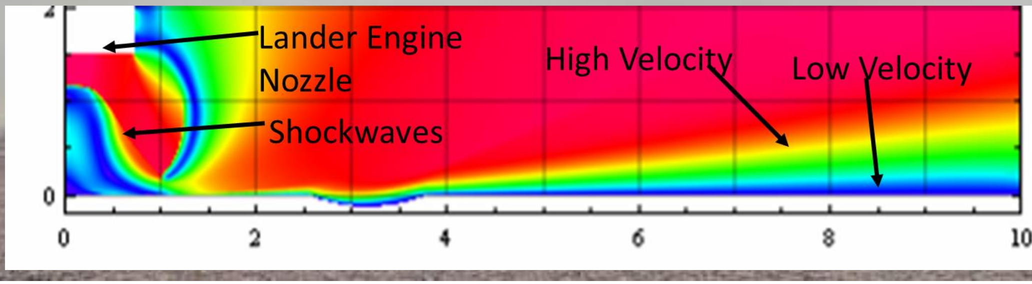




Construction of Consumables Depots for Crew & Power (O_2, H_2)

Launch / Landing Pad Construction

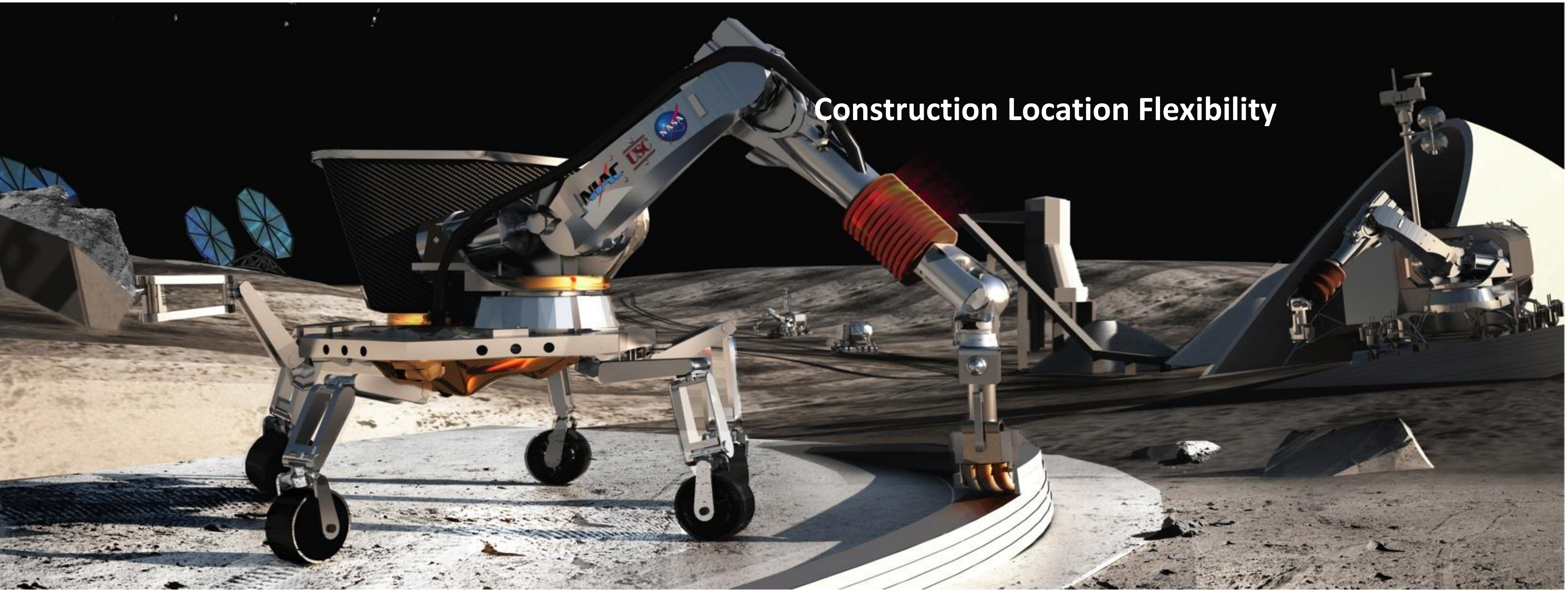
Construct a Launch/Landing Pad using In Situ Regolith for rocket plume impingement mitigation



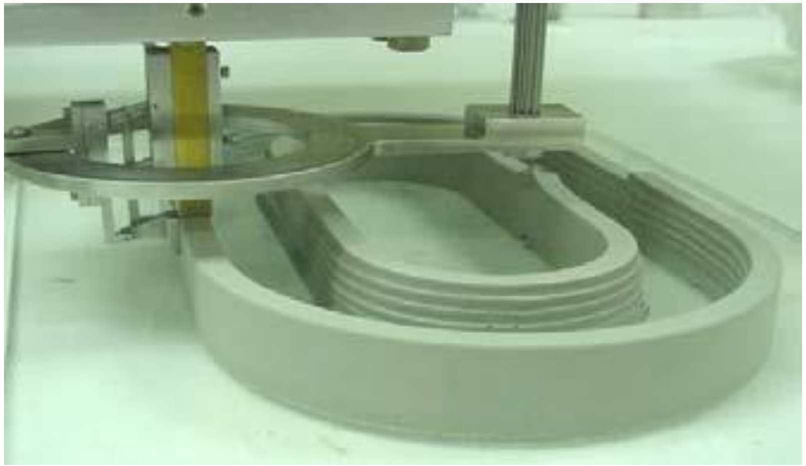
NASA Chariot Bull Dozer

Hawaii PISCES Rover on Mauna Kea with Payloads

3D Additive Construction with Regolith Concrete



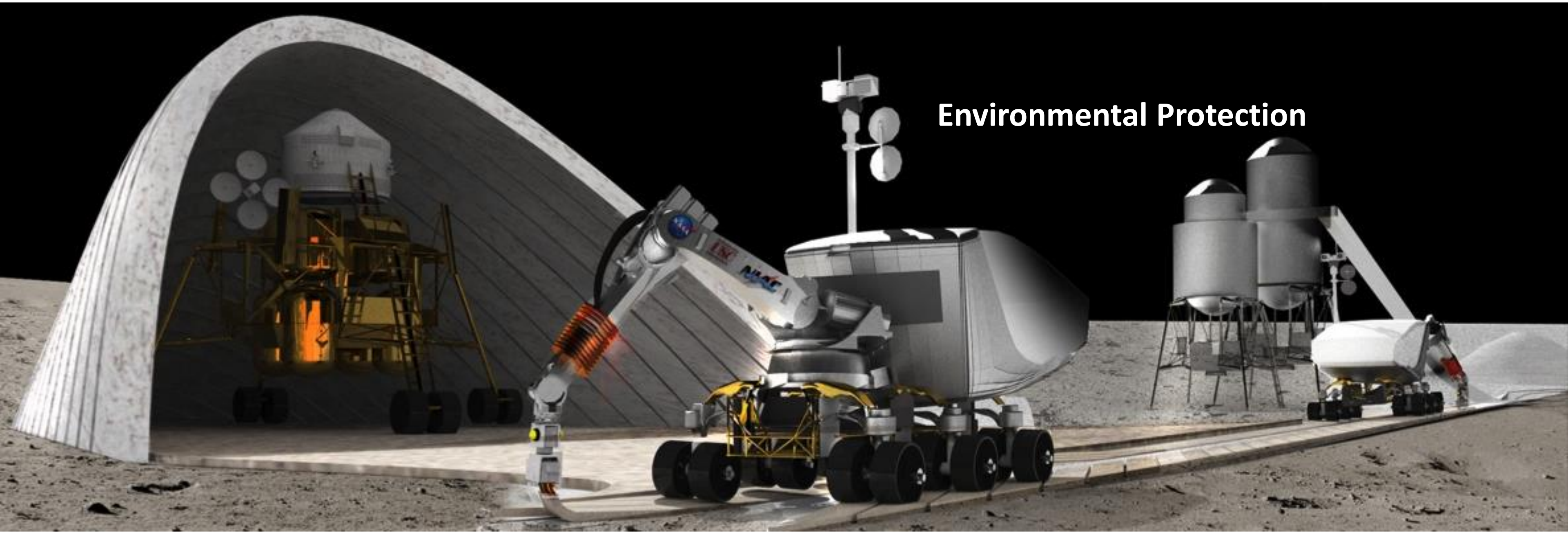
Multi-axis print head



Curved wall tool path development

Images Courtesy of Dr. B. Khoshnevis, Contour Crafting, LLC

3D Additive Construction Elements Using In-Situ Materials (Basalt)



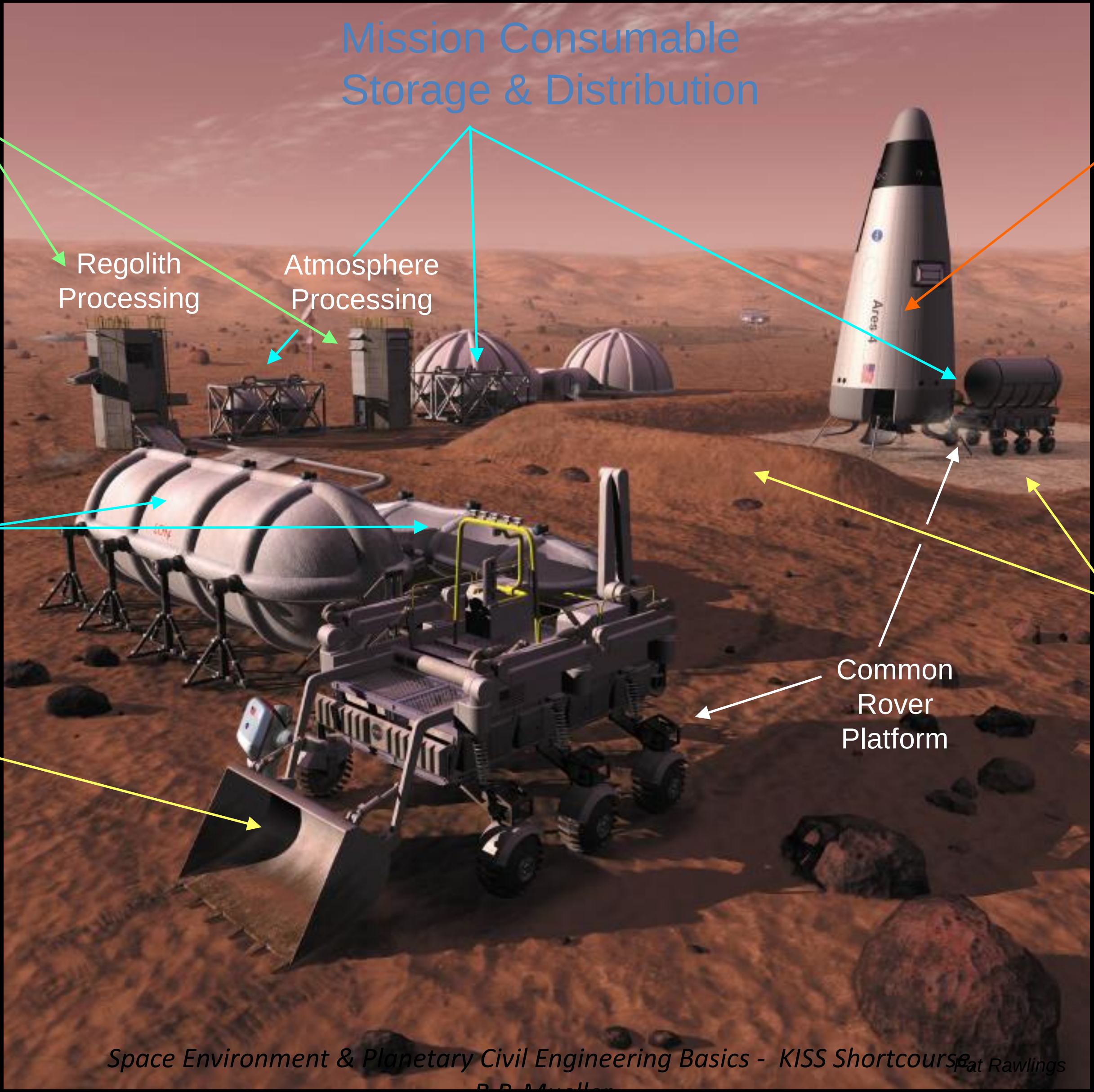
Complex Tool Path Development Allows Interior Walls

Mars Space Civil Engineering Capability Concepts

Resource Processing Plants

Collapsible/ Inflatable Cryogenic Tanks

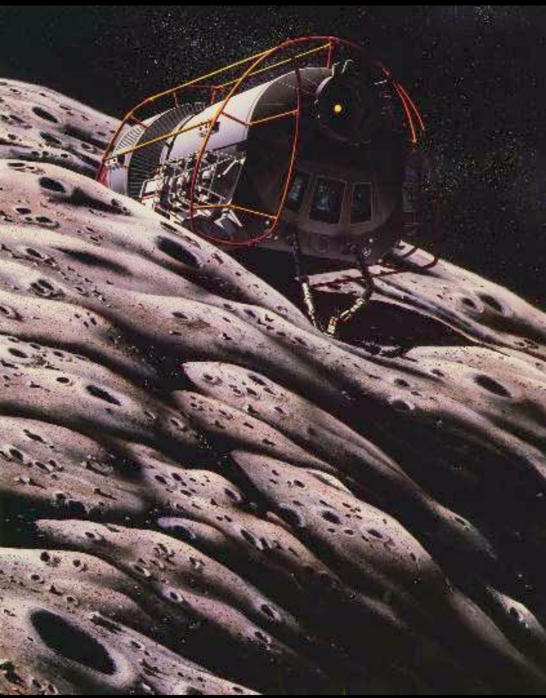
Multi-use Construction/ Excavator: resources, berms, nuclear power plant placement, etc.



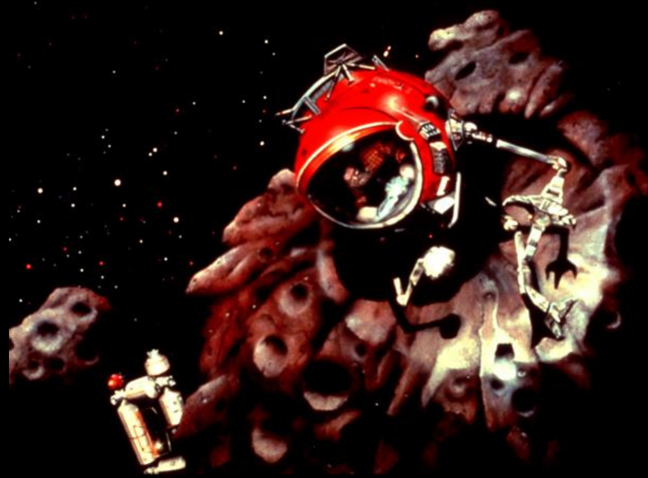
Reusable lander/ascent vehicle or surface hopper fueled with in-situ propellants

Landing pad & plume exhaust berm

NEO/Phobos Space Civil Engineering Capability Concepts



NEA 3D Additive Habitat Construction & Infrastructure



Resource Prospecting

Processing Captured NEO in Earth Orbit

Resource Mining on Phobos

Lunar Habitat Concept Example

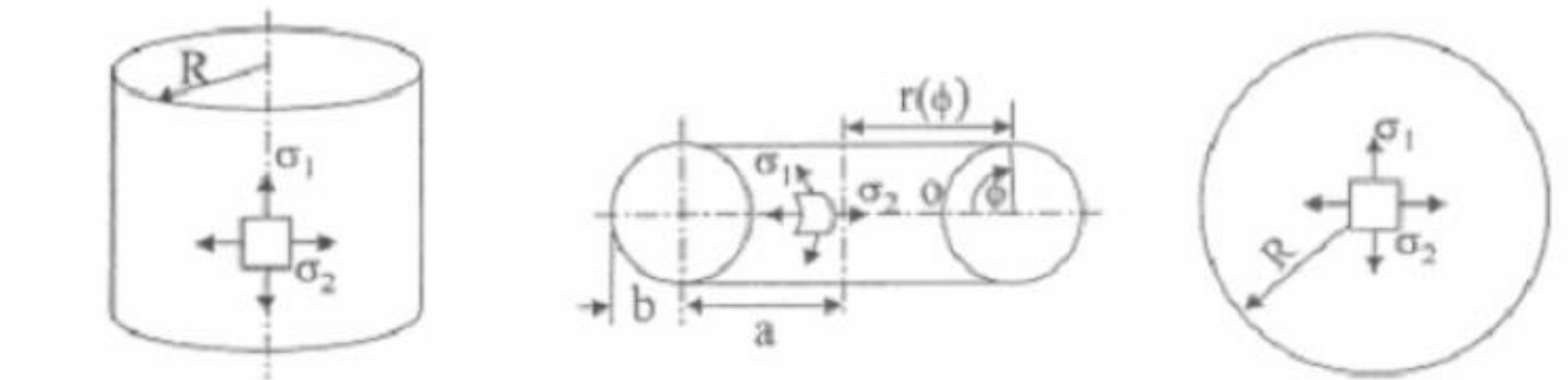
http://www.esa.int/var/esa/storage/images/esa_multimedia/images/2013/01/multi-dome_base_being_constructed/12502111-1-eng-GB/Multi-dome_base_being_constructed.jpg

Lunar Habitat Concept Example*

- Habitat internal pressure in the structure must be sufficient to sustain human life, so the structure becomes a pressure vessel – in Space, the pressurized habitat structure will be in tension – *not compression, as on Earth.*
- *Un-pressurized structures will be in compression*
- The internal pressure must be at least 26 (3.8 psi) (Aulesa, 2000) to 30 kPa (4.4. psi) (Langlais and Saulnier, 2000) to support human life and avoid altitude sickness, if it is composed purely of oxygen.
- Realistically, however, the pressure must be higher to make the living environment comfortable and avoid such effects as difficulty speaking and ineffective coughing (p.276 Eckart, 1999), and most importantly to reduce the extreme fire hazard that pure oxygen would cause.
- International Space Station (ISS) has an internal pressure of 101.3 kPa (14.7 psi) (Earth equivalent)
- Commonly assumed pressures for Space Habitats, atmospheric air have been "Denver Altitude Equivalent" of 82.7 kPa ~ 12 psi or as low as 68.9 kPa (10 psi)

*Jablonski, Alexander M., and Kelly A. Ogden. "A Review of Technical Requirements for Lunar Structures–Present Status." *Lunar Settlements* (2010): 451.

Shell Structures



Cylinder (R/t > 10)

$$\sigma_1 = \frac{qR}{t} \quad \sigma_2 = \frac{qR}{2t}$$

Toroid (b/t > 10)

$$\sigma_1 = \frac{qb}{2t}\frac{r(\theta) + a}{r(\theta)} \quad \sigma_2 = \frac{qb}{2t}$$

Sphere (R/t > 10)

$$\sigma_1 = \sigma_2 = \frac{qR}{2t}$$

Stresses are directly proportional to internal pressures

q = pressure, R= radius, t=thickness, a, b = toroidal radii

Kennedy, K.J., Raboin, J., Spexarth, G., Valle, G., "Inflatable Habitats," in *Gossamer Spacecraft: Membrane and Inflatable Technology for Space Applications*, edited by Jenkins, C.H.M., American Institute of Aeronautics and Astronautics, Inc., Virginia. 2001, pp.527-552

Lunar Habitat Concept Example*

- The internal pressure of the structures will create substantial tensile loads on the structure. The regolith piled on the structure for shielding will somewhat counter the load on the top.
- However due to the reduced lunar gravity, the pressure caused by its weight will not be greater than the internal pressure.
- Assume the regolith shield is 5.4 m high, gravity is 1.62 m/s^2, and the density of regolith is between 1.3 (Aulesa et al, 2000) and 1.75 g/cm^3 (Sadeh et al, 2000)
- The pressure created by the regolith will be between 11.4 and 15.9 kPa, which is much less than the minimum required internal pressure for human life, of 26 to 30 kPa (Aulesa, 2000; Langlais and Saulnier, 2000).
- There will be also horizontal loads on the structure due to the pressure, which the regolith will not counter.
- Typical non-reinforced Portland Cement concrete tensile strengths are only 2.0 MPa, (300 psi) – 5.0 MPa, (700 psi) – which is very low. (wood ~ 1,600 psi bending)
- ***Lunar Concrete must be stronger (or reinforced) if used in tension or bending***

*Jablonski, Alexander M., and Kelly A. Ogden. "A Review of Technical Requirements for Lunar Structures–Present Status." *Lunar Settlements* (2010): 451.

Bounding Case: Regolith for Radiation Shielding

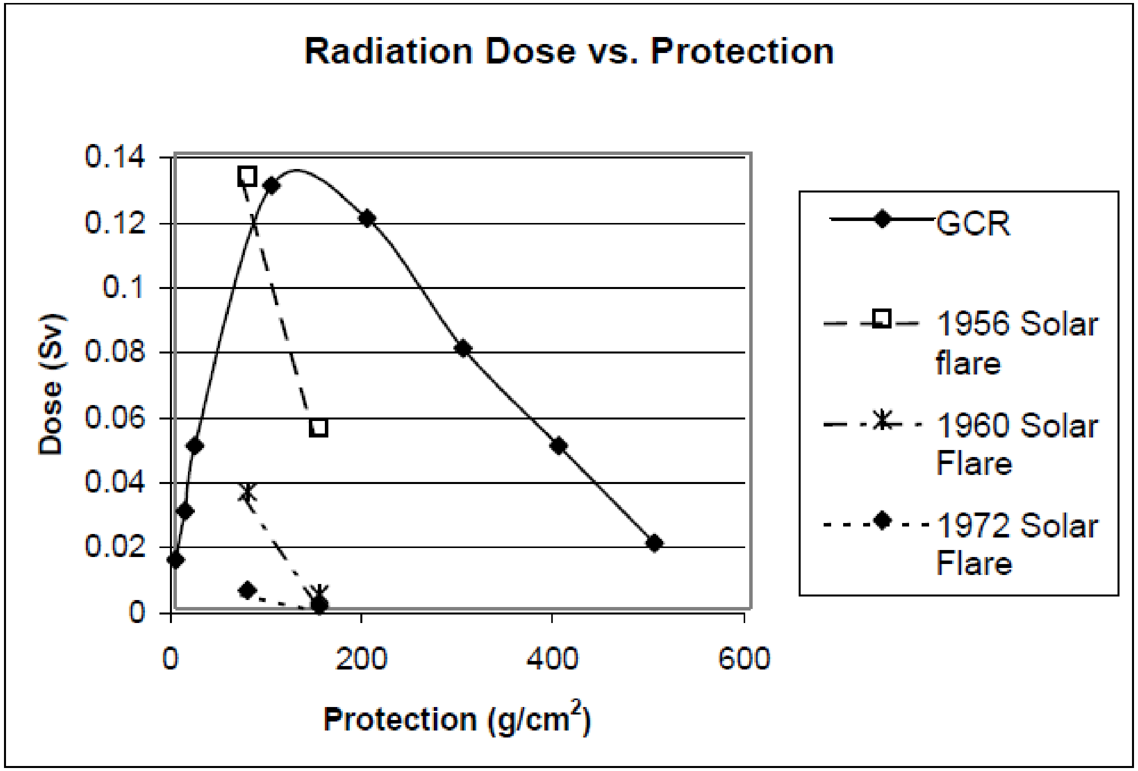


FIGURE A-1. Radiation dose as thickness of regolith increases, derived from (Aulesa, 2000; Lindsey, 2003)

Equivalent Shielding to Earth at Sea Level = 1,000 g/cm^2 (7.7 m regolith thickness)
Minimum acceptable shielding = 700 g/cm^2 (5.4 m regolith thickness)

Assuming bulk density of 1.3 g/cm^3

Jablonski, Alexander M., and Kelly A. Ogden. "A Review of Technical Requirements for Lunar Structures–Present Status." *Lunar Settlements* (2010): 451.

Top Robotic Technical Challenges*

- Object Recognition and Pose Estimation
- Fusing vision, tactile and force control for manipulation
- Achieving human-like performance for piloting vehicles
- Access to extreme terrain in zero, micro and reduced gravity
- Grappling and anchoring to asteroids and non cooperating objects
- Exceeding human-like dexterous manipulation
- Full immersion, telepresence with haptic and multi modal sensor feedback
- Understanding and expressing intent between humans and robots
- Verification of Autonomous Systems
- Supervised autonomy of force/contact tasks across time delay
- Rendezvous, proximity operations and docking in extreme conditions
- Mobile manipulation that is safe for working with and near humans

*(no specific order)

NASA Technology Area 4 Roadmap: Robotics, Tele-Robotics and Autonomous Systems (NASA, Ambrose, Wilcox et al, 2010)

Top Space Mining/Construction Technical Challenges*

- Strength of In-situ derived regolith concrete materials
- New construction methods & equipment
- Low reaction force excavation in reduced and micro-gravity
- Operating in regolith dust
- Fully autonomous operations
- Energy re-charging and work flow scheduling
- Encountering sub surface rock obstacles
- Long life cycle (5-10 years) and high reliability required
- Spare parts logistics, manufacturing and repair
- Unknown water ice / regolith composition and deep digging
- Operating in the dark cold traps of perennially shadowed craters
- Extreme access and mobility
- Extended night time operation and power storage
- Thermal management
- Robust communications

*(no specific order)

Summary

- There are vast amounts of resources in the solar system that will be useful to humans in space and possibly on Earth
- None of the regolith resources can be harnessed without the first necessary step of extra-terrestrial mining
- Space faring humans will need planetary bases which will require planetary surface construction
- Space robots for mining/construction operate in unique environments and have design constraints requiring innovative designs
- Much more work is needed before Space Mining and Planetary Surface Construction become viable, but *the first commercial space companies are emerging today*

- **New technologies such as 3D Additive Construction using In-Situ Resources could be an enabling Game Changer**