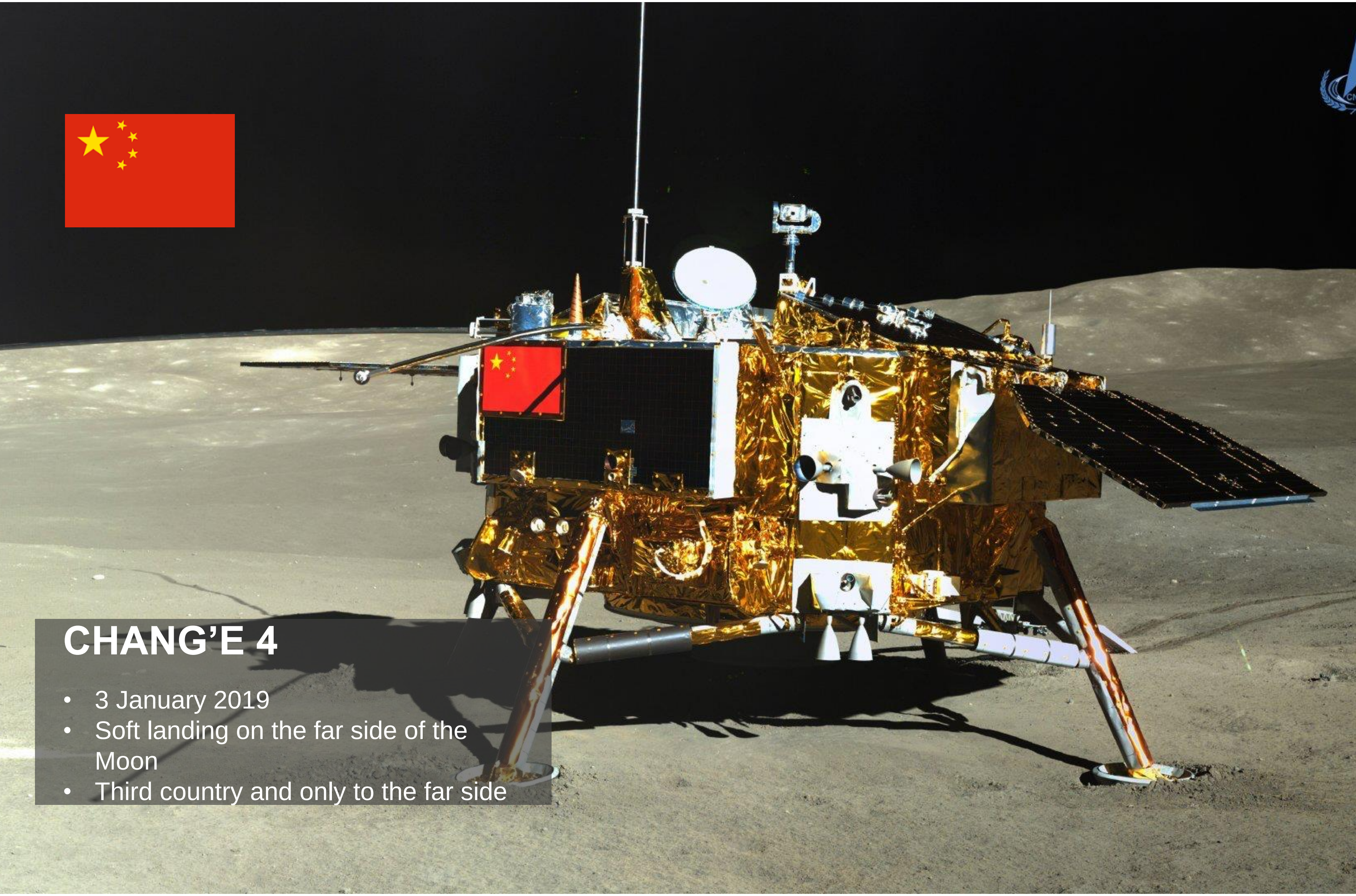
School of Minerals and Energy Resources Engineering

Off-Earth Mining

Recently in the news…



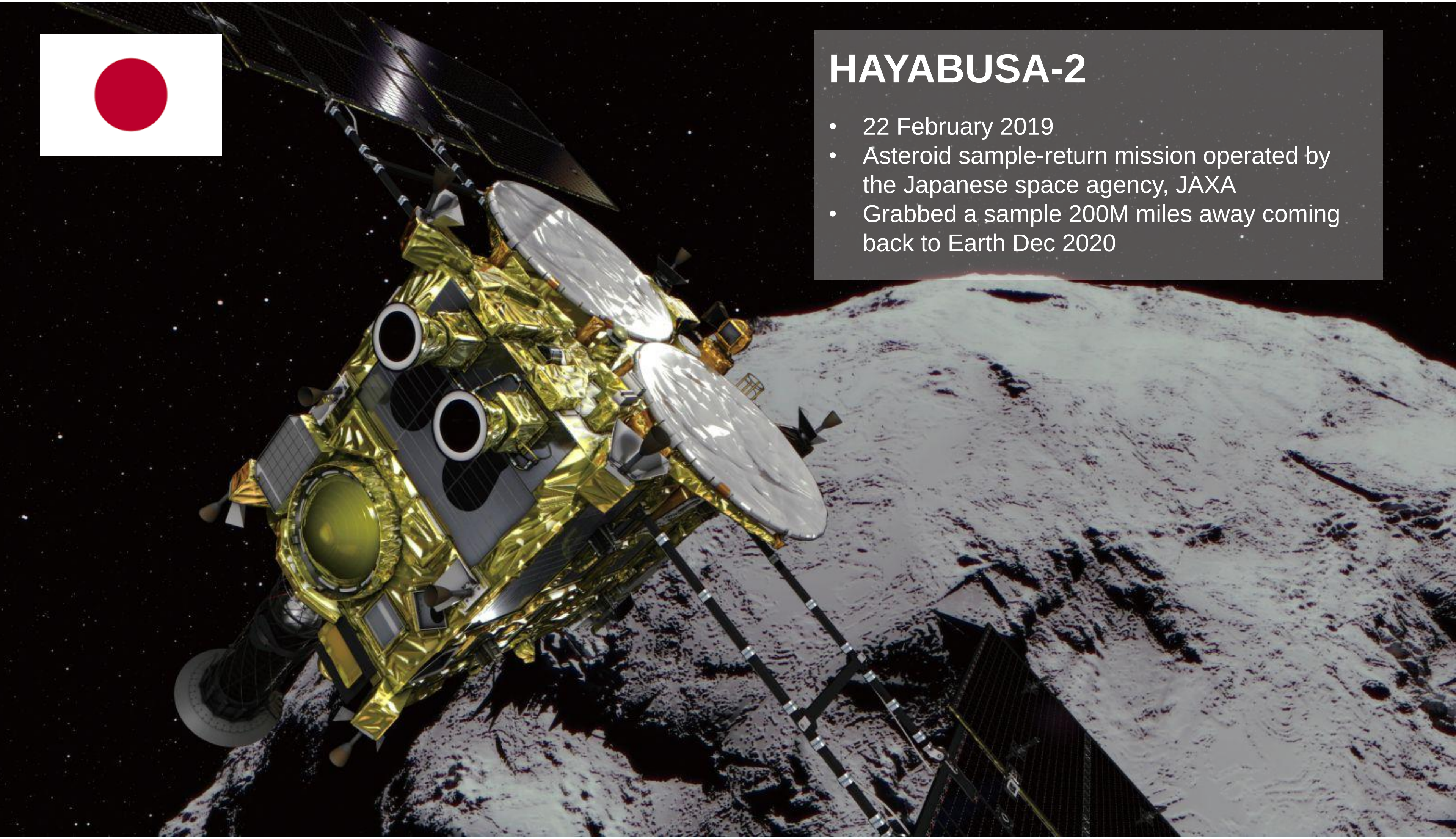
CHANG’E 4

- 3 January 2019
- Soft landing on the far side of the Moon
- Third country and only to the far side

NASA CLPS

- 9 Companies Selected
- $2.3 Billion approved in NASA Budget
- 12 payloads ready to go for 2020

HAYABUSA 2



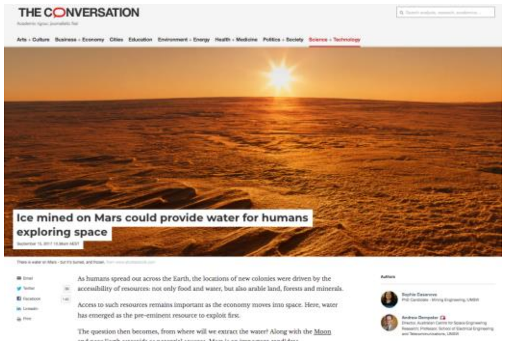
HAYABUSA-2

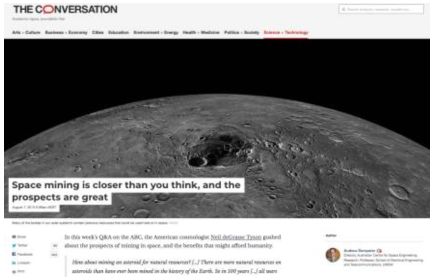
- 22 February 2019
- Asteroid sample-return mission operated by the Japanese space agency, JAXA
- Grabbed a sample 200M miles away coming back to Earth Dec 2020

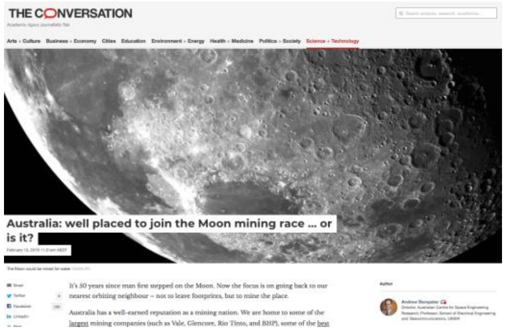
SPACE IL

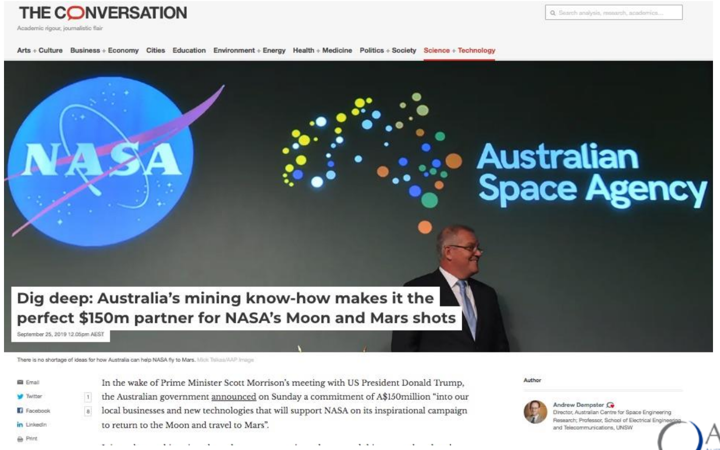
SPACE IL (crashed!)
- 22 February 2019
- Google Lunar XPRIZE finalist
- Launched on a SpaceX Falcon 9 rocket

Socialisation of Space Resources









Off-Earth MINING

- Engineers like to overcome challenges.
  - gravity, inertia, energy, materials handling, friction, temperature and so on …
- What mining method will we be using?
- None of the current methods will be applicable.
  - May be strip mining for lunar regolith as in surface coal.

UNSW SYDNEY

The Motivation

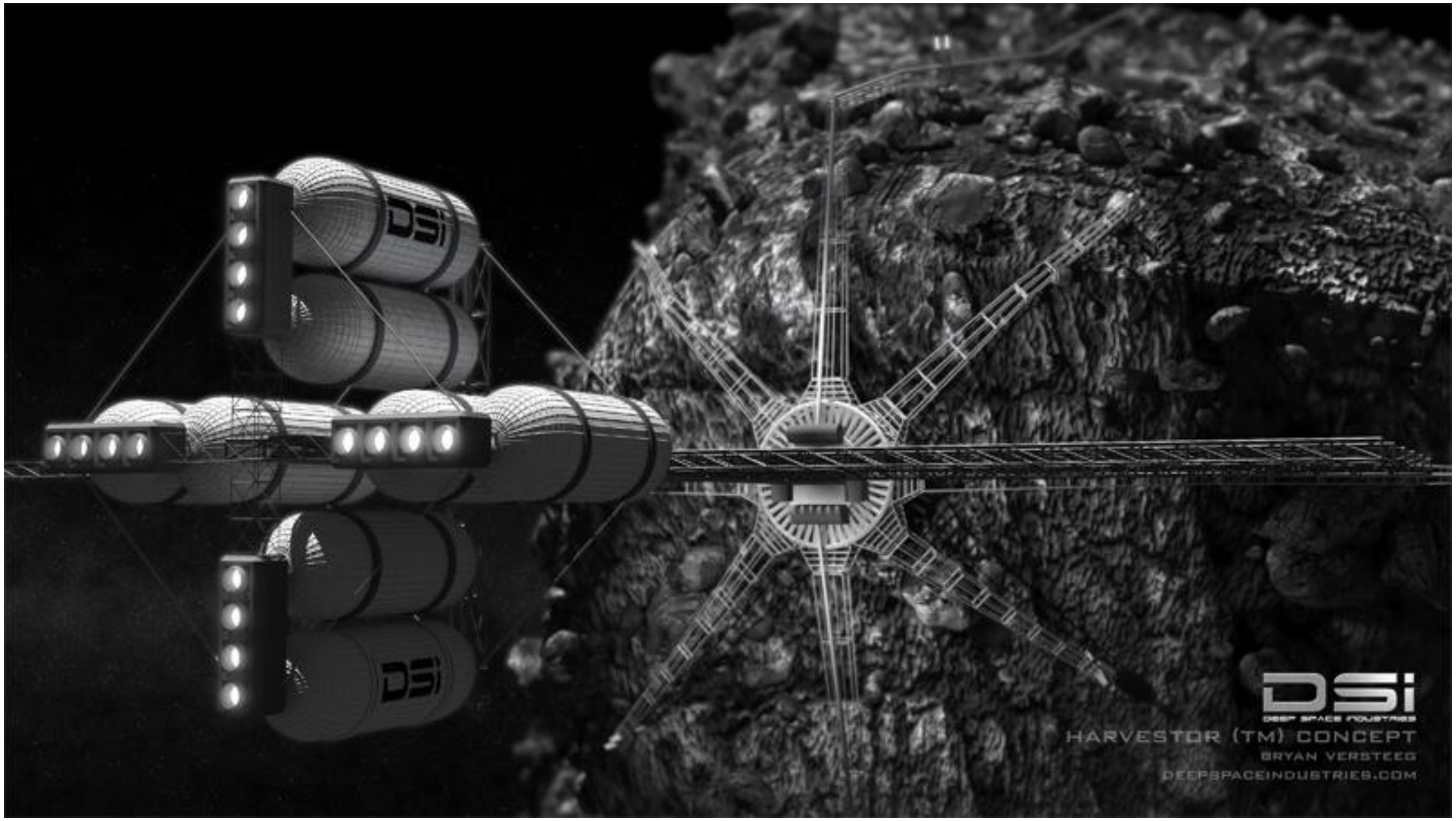
- *"**Where she be, there she be**"* - there are valuable minerals to be mined, adventurous humans will arrive in crowds – even combatting with extreme conditions and excessive risks!
- An ***abundance of valuable resources*** that can feed our technologically driven society,
- the necessity and demand of discovering new places that ***our society can colonise***,
- the development of new technologies and processes to enable these missions will ***create spin-off technologies*** that can be used in our terrestrial operations.

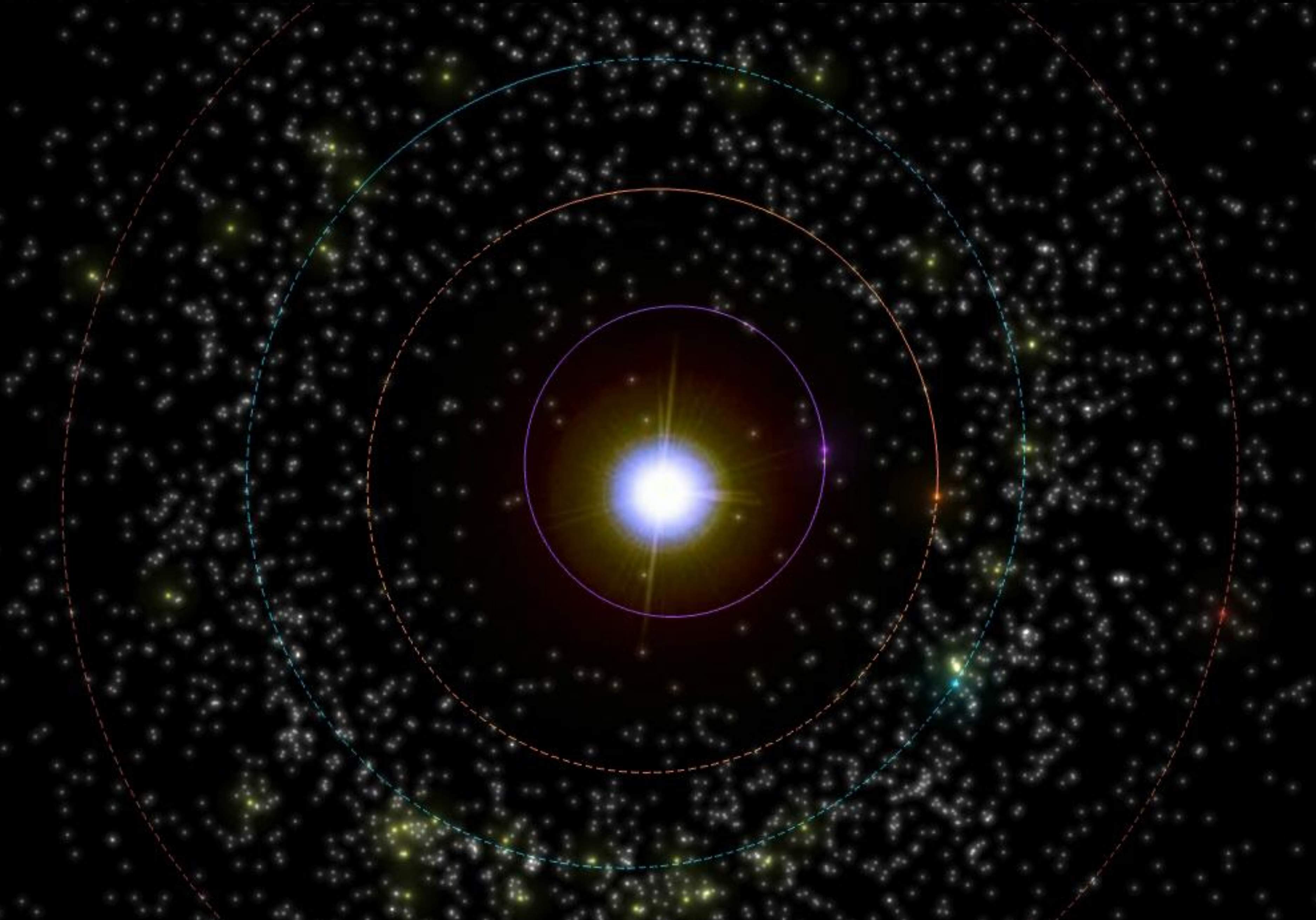
Target Bodies for Off-Earth Mining

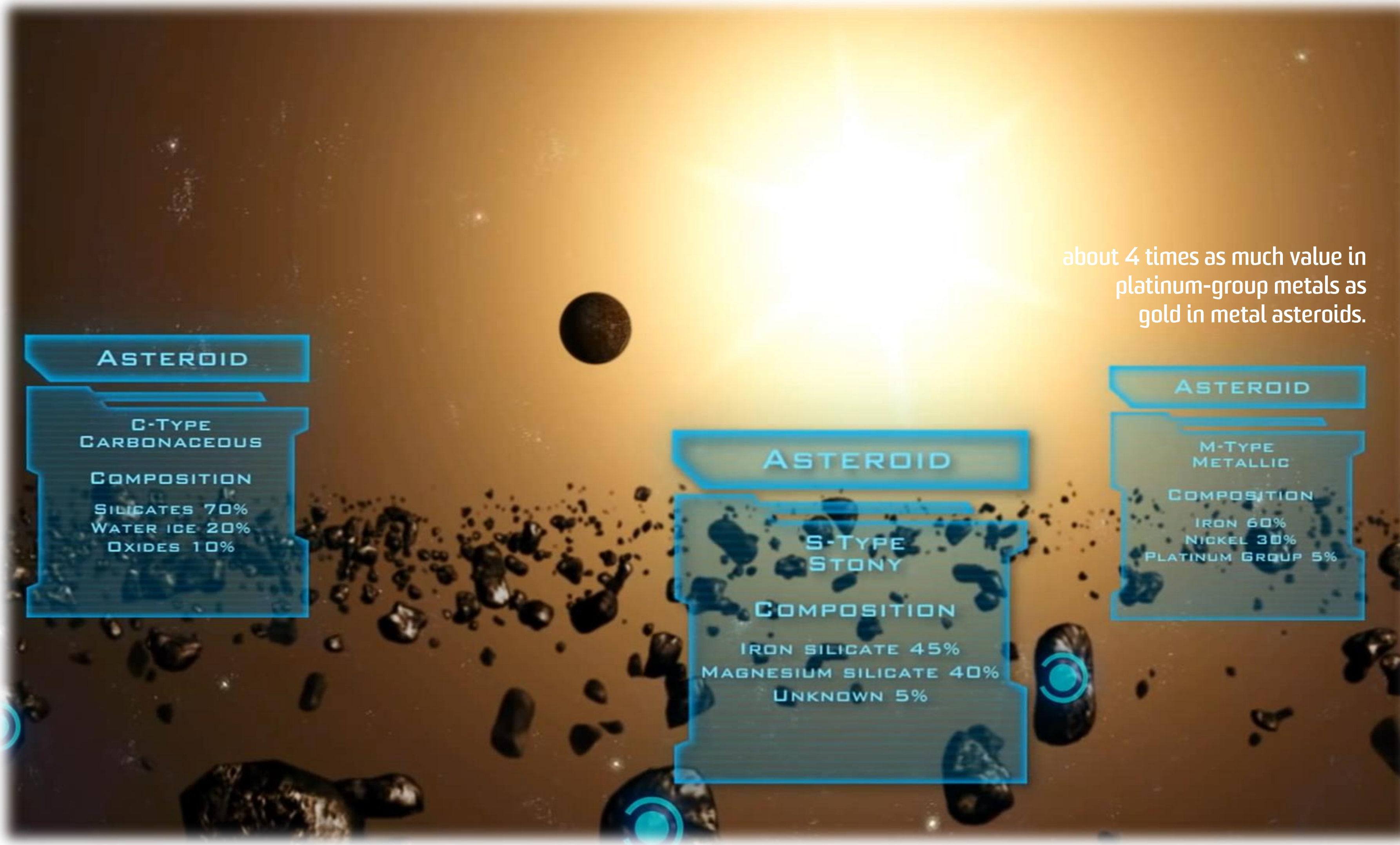
Commercial opportunities will include the mining of

- Asteroids,
- Comets,
- the Moon,
- Mars, and
- Mars' Moons

Asteroids & Comets







about 4 times as much value in platinum-group metals as gold in metal asteroids.

http://deepspaceindustries.com

An investigation into the feasibility of mining off-earth minerals, with a focus on sourcing from asteroids by G Craig, S Saydam & A Dempster

1986 DA

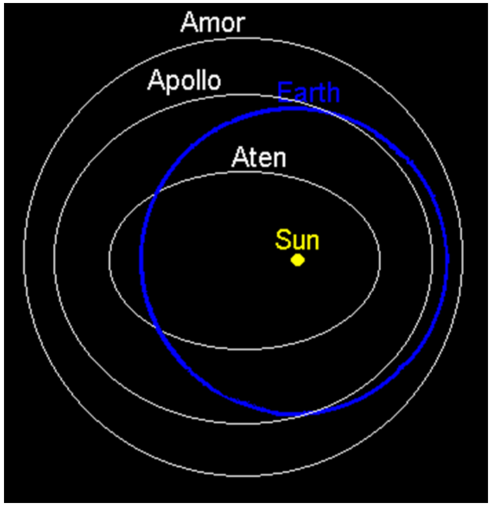
M-type asteroid 88% Fe, 10% Ni, 0.5% Co *(Ingebretsen, 2001).*

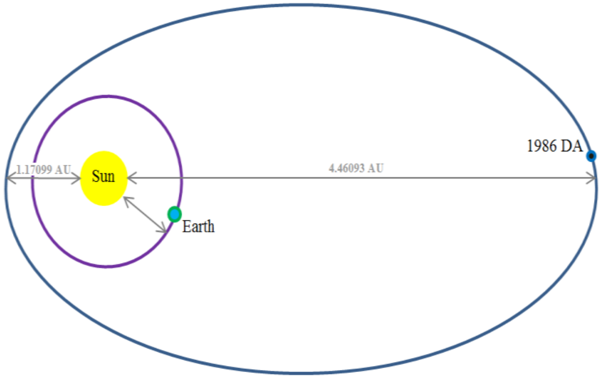
- It is essentially made up of *"naturally occurring stainless steel"*

2.3 km diameter.

0.5 Astronomical Units (AU) away (75Mkm) from Earth, periodically.

Approximately, 8 months to travel between Earth and the asteroid, similar to the Mars.





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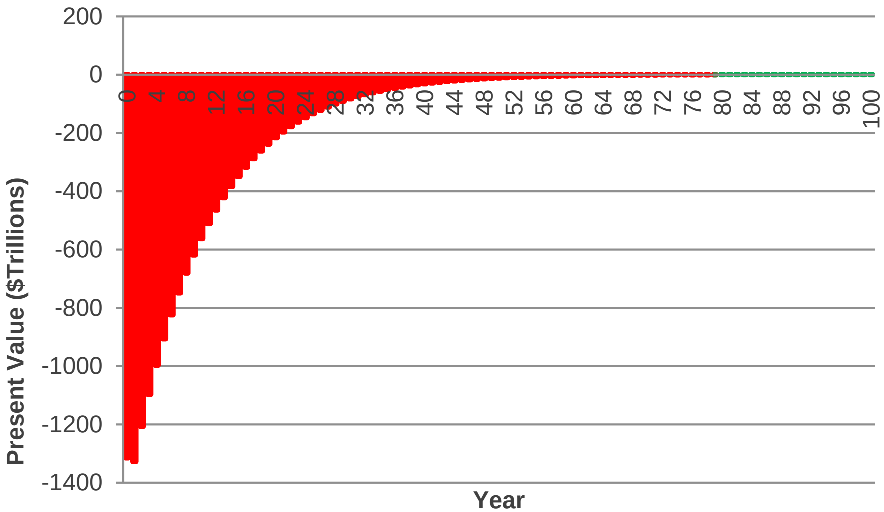
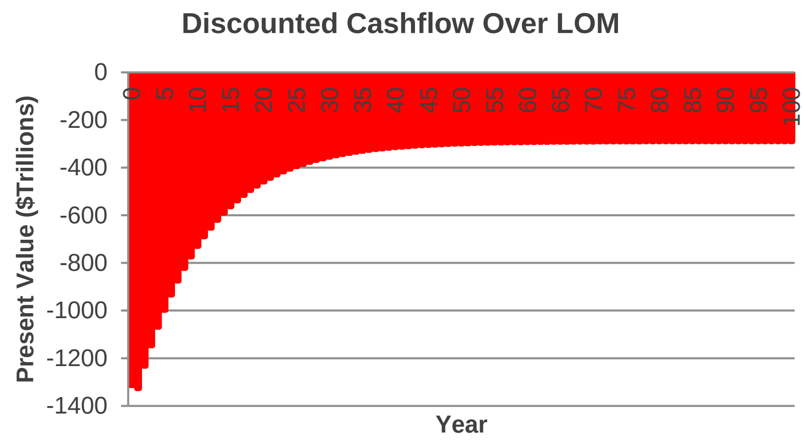
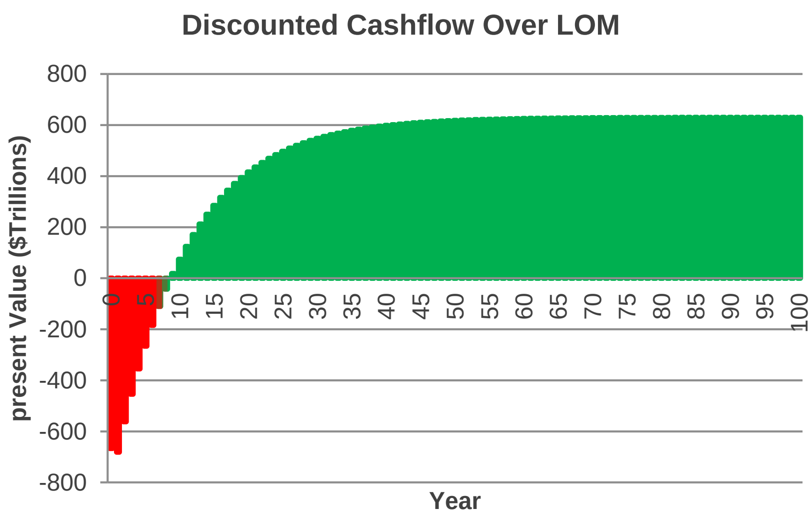
Base Case: 100% returns to Earth



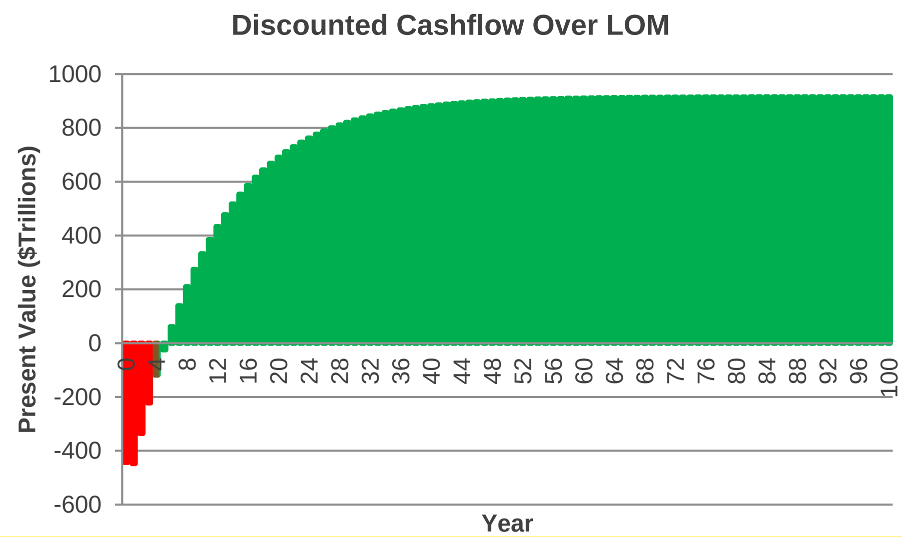
Case Study 1: 80% of mined product is sold



Case study 2: Asteroid is half the distance from Earth



Case Study 3: Market is near 1986 DA



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The Moon

and its Dormant Potential

ispace

Resources on the Lunar Surface

The Moon is Rich in Resources

ispace is aware through all the missions from NASA, ESA, JAXA, among others, about the abundance of resources on the moon including;

Fe Mg Th U

Al Ca Si K REE P

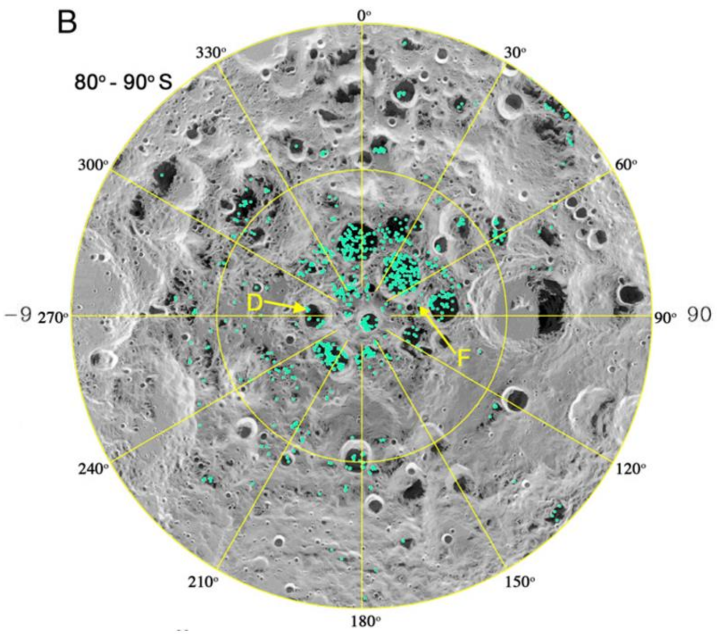
H_2O Ti

Na H O

ispace

The Moon

Resource Maps



Estimated 3-6 billion tons of H_2O

(Shuai Lia et all, 2018)

ispace

UNSW SYDNEY

The Moon is rich in resources

Resources on the Lunar Surface

ispace is aware through all the mission from NASA, ESA, JAXA, among others, about all the abundant resources on the moon including;

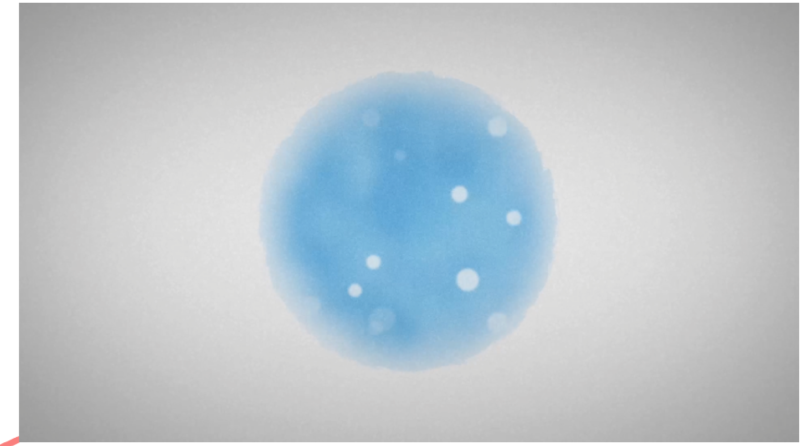
Fe	Mg	Th	U		
Al	Ca	Si	K	REE	P
H_2O	Ti				
Na	H	O			

H2O can be used for **rocket propellant**, drinkable water, and oxygen for life support. **ULA (United Launch Alliance)** has offered to pay **3,500 US$/kg** of fuel (H,O) in LEO, and **500 US$/kg** on the moon.

ispace

The Moon

Resource Maps



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Initial Potential Propellant Customers

Space Agencies and Rocket Companies:

- ULA (United Launch Alliance)
- Lockheed Martin
- Boeing
- NASA
- ESA
- ROSCOSMOS
- JAXA
- SPACE X
- VIRGIN GALACTIC
- ROCKET LAB
- AIRBUS

Customers at different orbits/locations:

- LEO
- GEO
- EML1
- Moon

Commercial Lunar Propellant Architecture: A Collaborative Study of Lunar Propellant Production (David Kornuta et all, 2018)

Table 11: Cost of propellant from Earth or the Moon

	From Earth	From Moon
Earth Surface	$ 1/kg	-
LEO	$ 4,000/kg	$3,000/kg
GTO	$ 8,000/kg	$1,500/kg
GEO	$16,000/kg	$1,500/kg
EML1	$12,000/kg	$1,000/kg
Lunar Surface	$36,000/kg	$500/kg

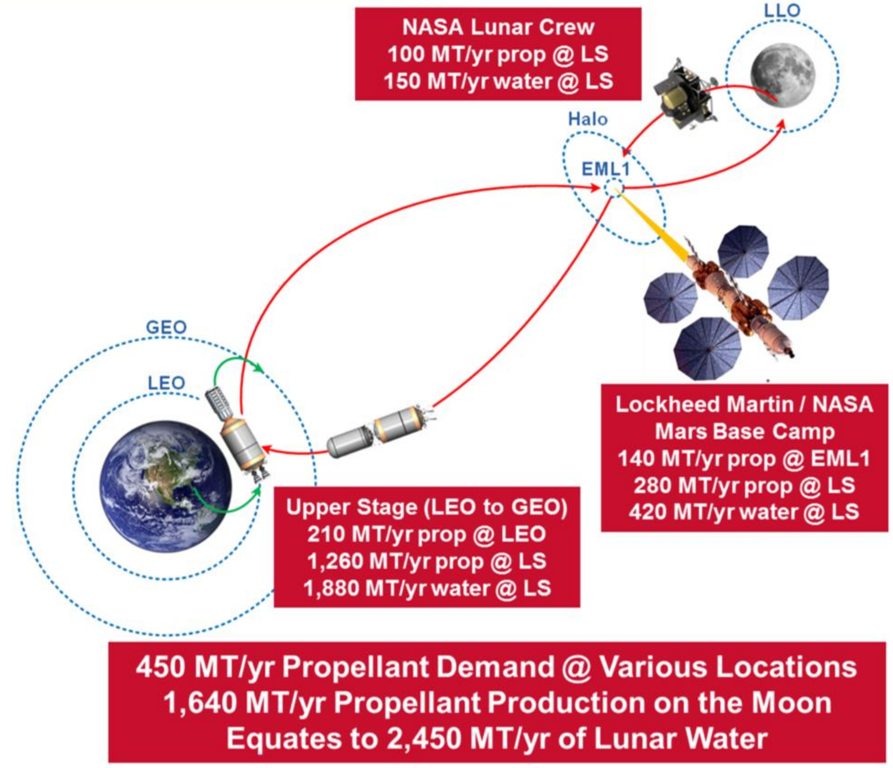


Figure 68: Initial Lunar Propellant Customers

Exploring and Mining on
The Moon Environment

- Develop Completely New Technology
- Co-develop Currently Needed Technology

No atmosphere
No (O, N, C)

Temperatures
Day Time (127 C)
Night Time (-173 C)
Craters (-238 C)

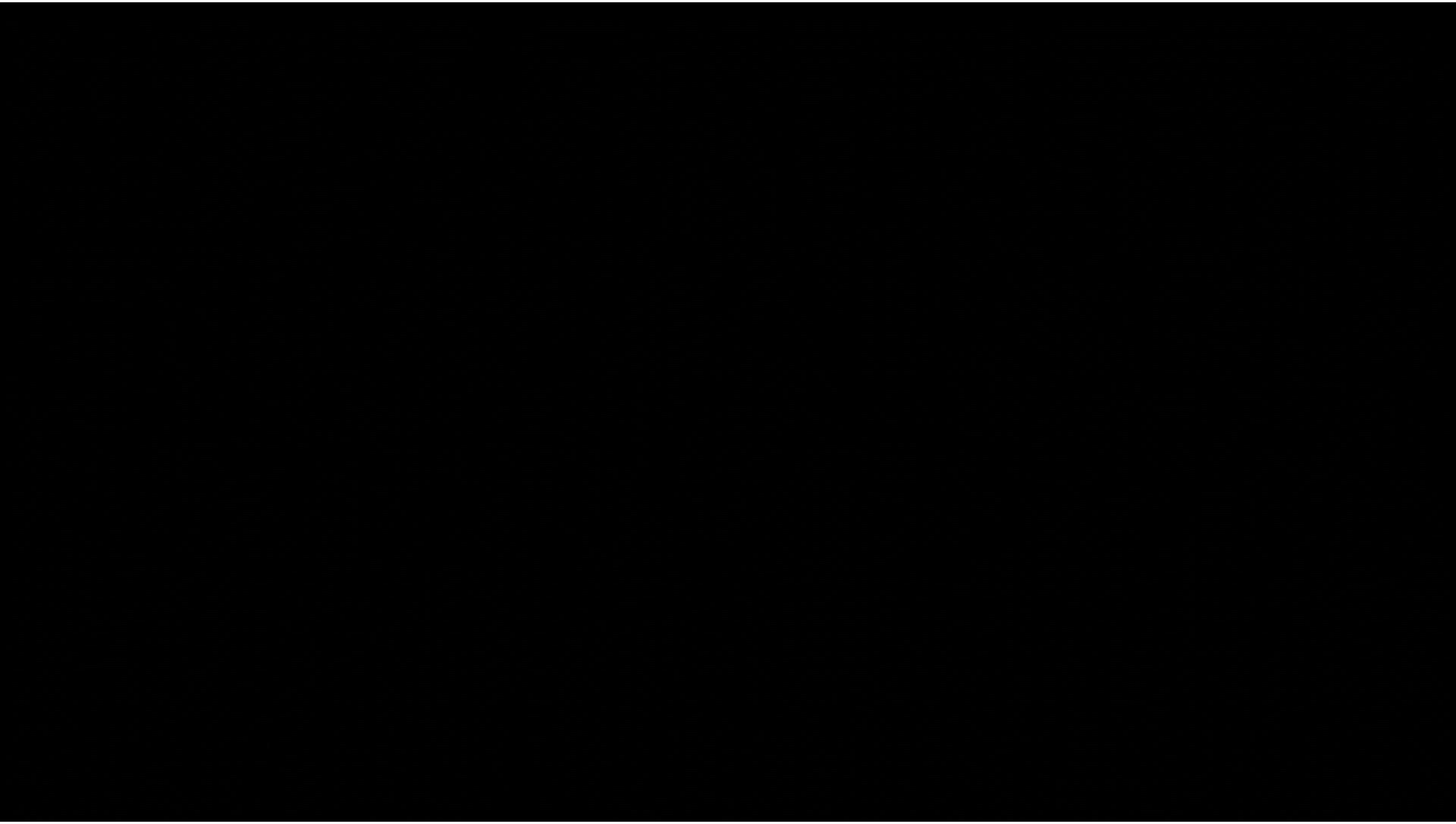
Lunar Day / Night
13.5 Earth Days / Nights

Hard and
Abrasive Material

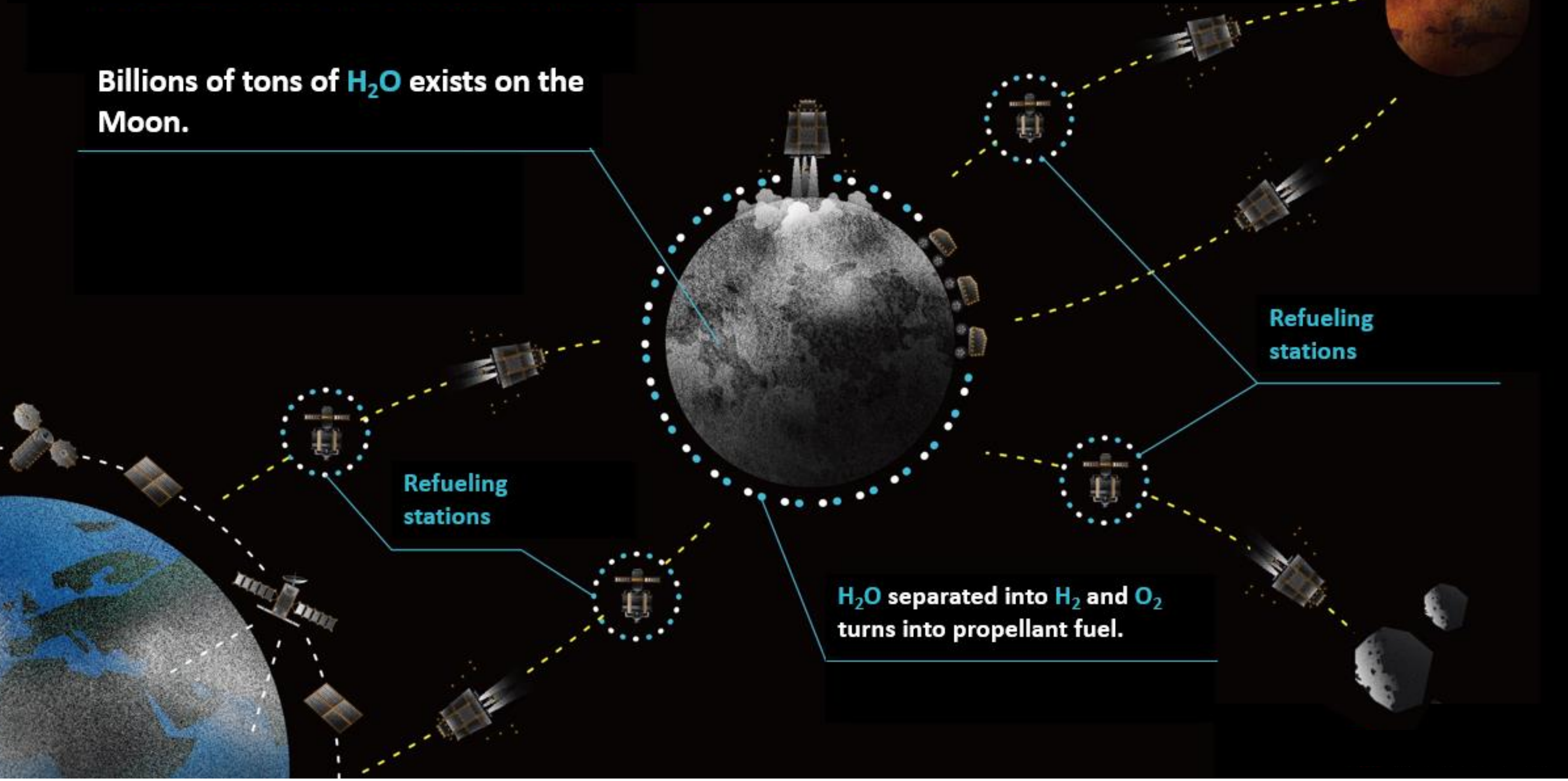
Gravity (1/6 of Earth)

ispace

To expand our social and economic sphere to the Moon

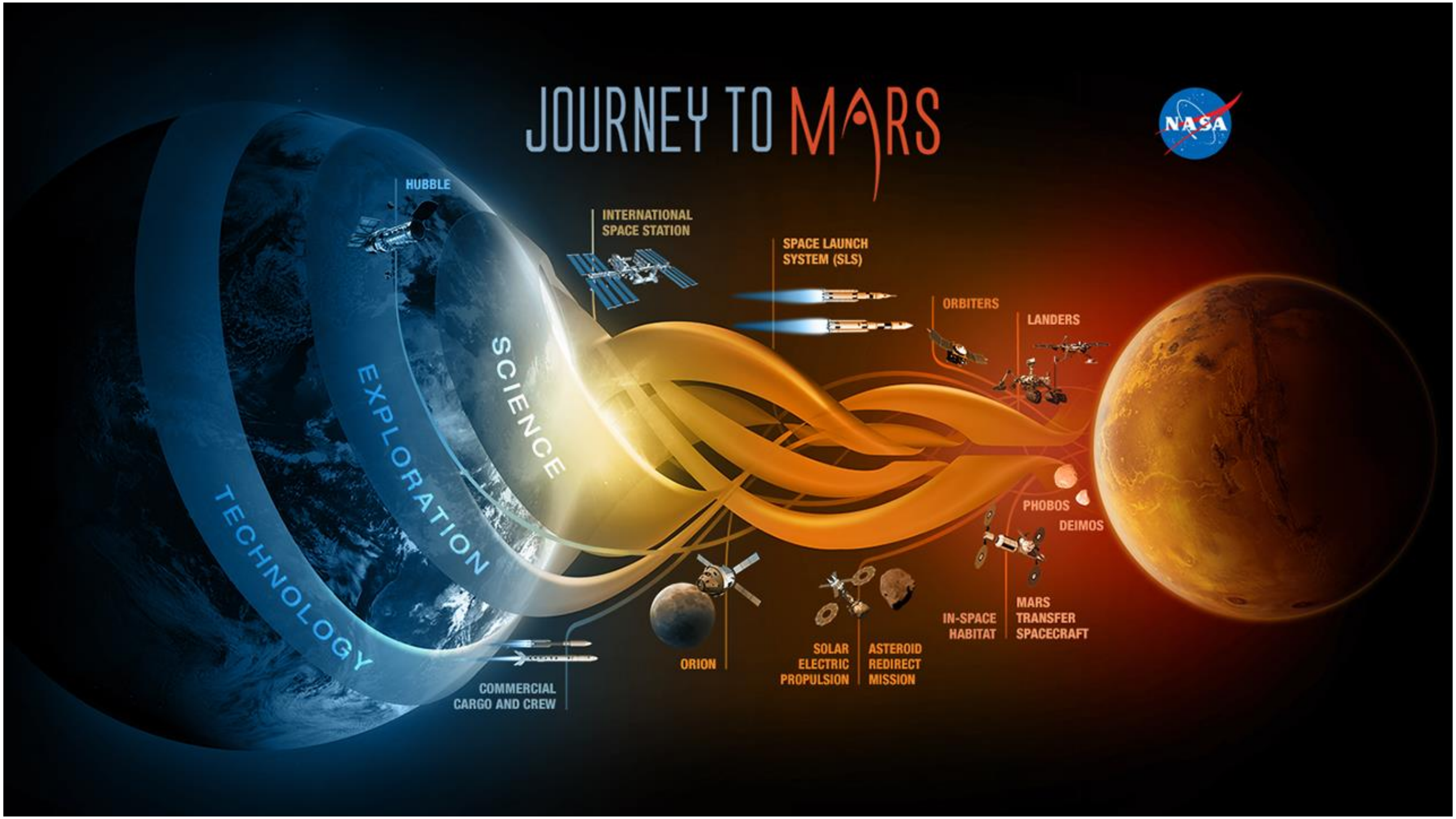


To prospect water & natural resources, and establish fuel station in cislunar space

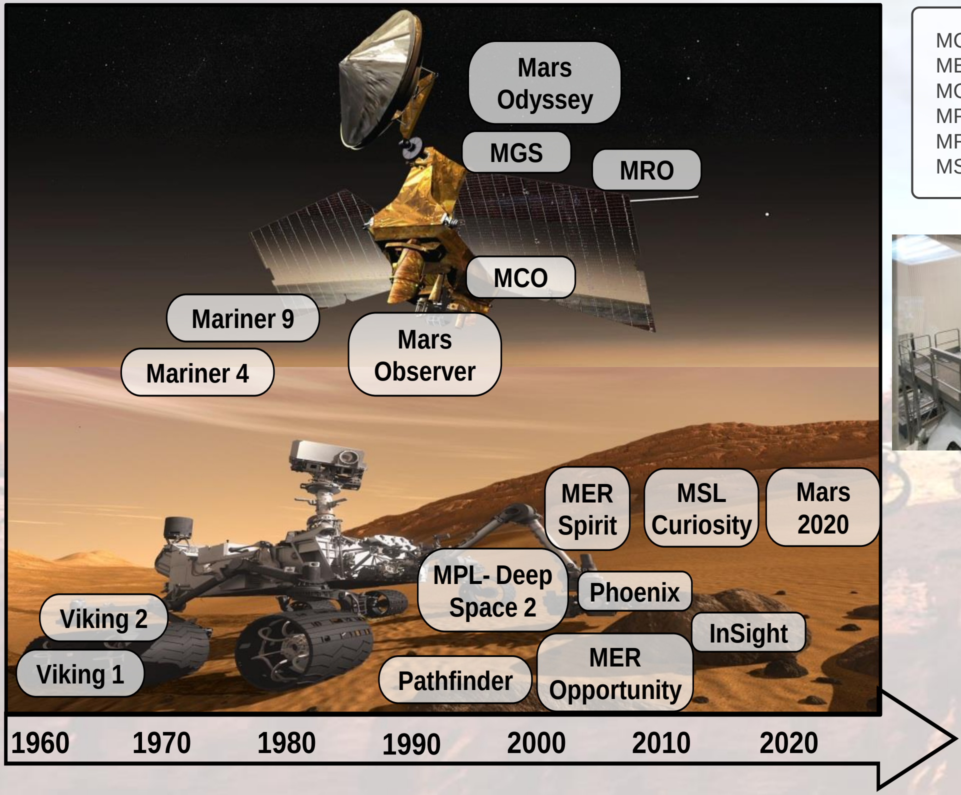


"While far away, Mars is a goal within our reach. We are closer to sending humans to Mars than at any point in NASA's history."

Journey to Mars, NASA (2015)

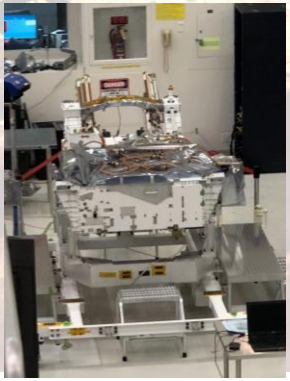

JOURNEY TO MARS
NASA
HUBBLE
INTERNATIONAL SPACE STATION
SPACE LAUNCH SYSTEM (SLS)
ORBITERS
LANDERS
SCIENCE
EXPLORATION
TECHNOLOGY
PHOBOS
DEIMOS
MARS TRANSFER SPACECRAFT
IN-SPACE HABITAT
SOLAR ELECTRIC PROPULSION
ASTEROID REDIRECT MISSION
ORION
COMMERCIAL CARGO AND CREW

Mars Exploration Evolution

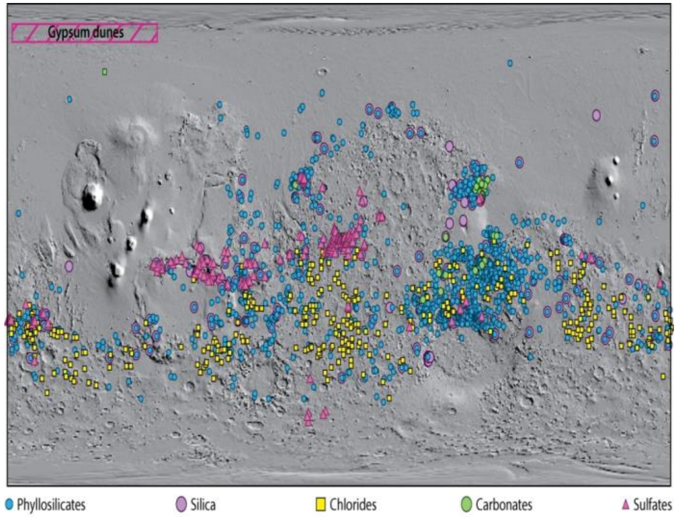


Modified from NASA, 2015

MCO:	Mars Climate Orbiter
MER:	Mars Exploration Rover
MGS:	Mars Global Surveyor
MPL:	Mars Polar Lander
MRO:	Mars Reconnaissance Orbiter
MSL:	Mars Science Laboratory

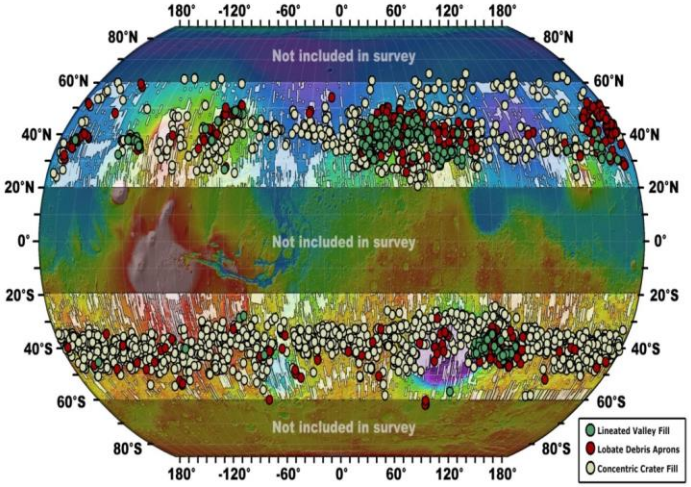


Location of Water Resources on Mars



A master compilation of hydrated mineral detections for Mars

From Ehlmann and Edwards (2014)

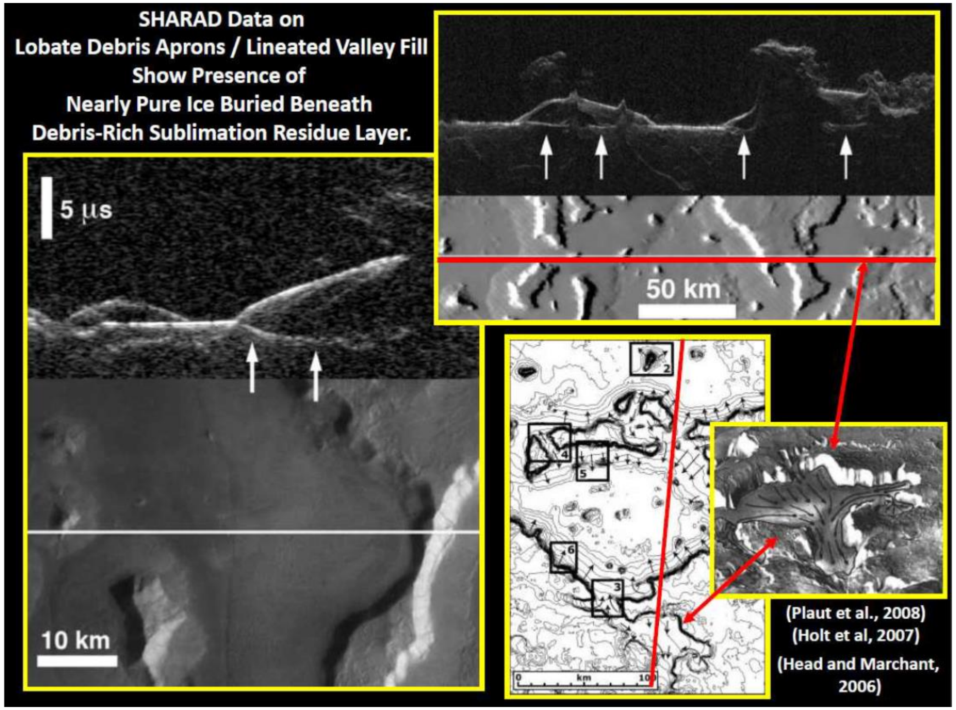


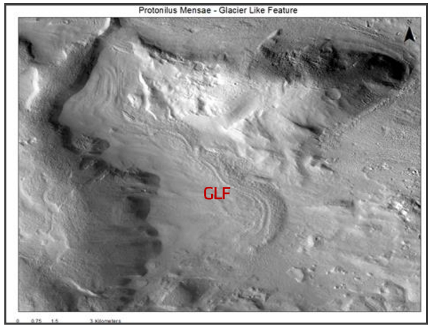
Location of identified mid-latitude glacial landforms

From Dickson et al., 2012

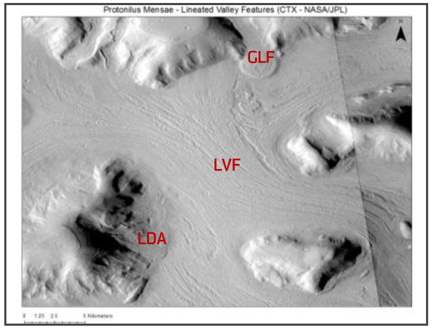
Source: S Casanova

Debris Covered Glaciers





Glacier Like Feature (GLF)



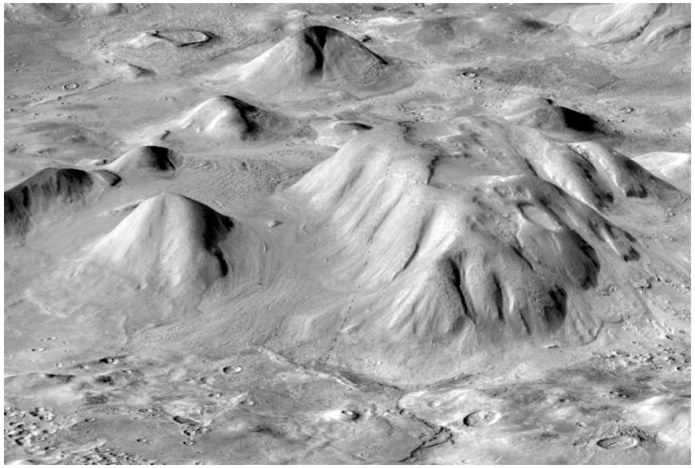
Lobate Debris Aprons (LDA) &
Lineated Valley Fill (LVF)

Source: S Casanova

Variability of Martian Terrain

Kimberley Formation - Gale Crater (Credit: NASA/JPL)

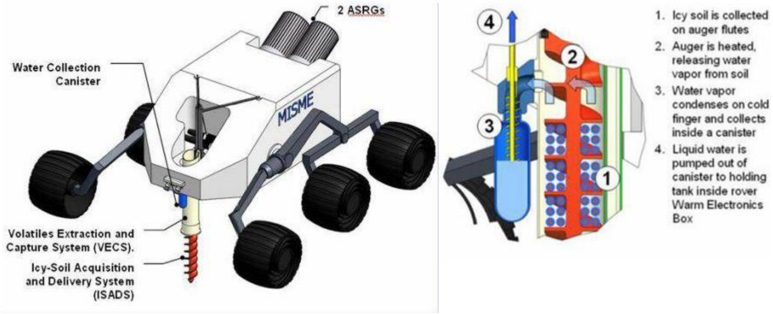
Namib Dune - Gale Crater (Credit: NASA/JPL)



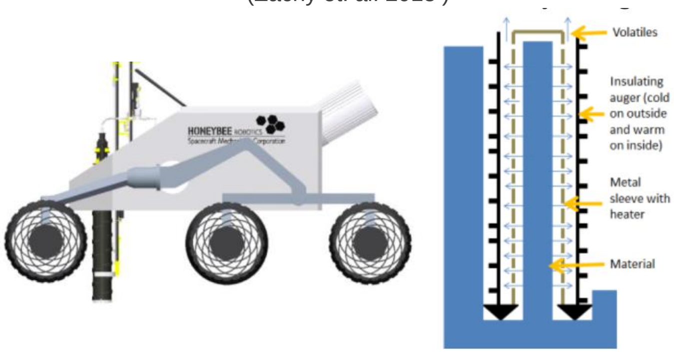
Mid-latitude - Debris Covered Glaciers of the Protonilus Mensae 3D visualisation of HRSC DTM (h2908_0000.da4) (2x exaggeration) with CTX draped imagery (P03_002190_2213_XN41N307W & J03_045797_XN_42N307W)

Source: S Casanova

Proposed Water Excavation and Extraction Designs



Honeybee Robotics - Mobile in-situ water Extractor (MISWE) (Zacny et. al. 2015)



Honeybee Robotics – Planetary Volatiles Exploration Corer (PvEX Core) (Zacny et. al. 2016)

RASSOR Prototype Excavator (NASA - KSC)

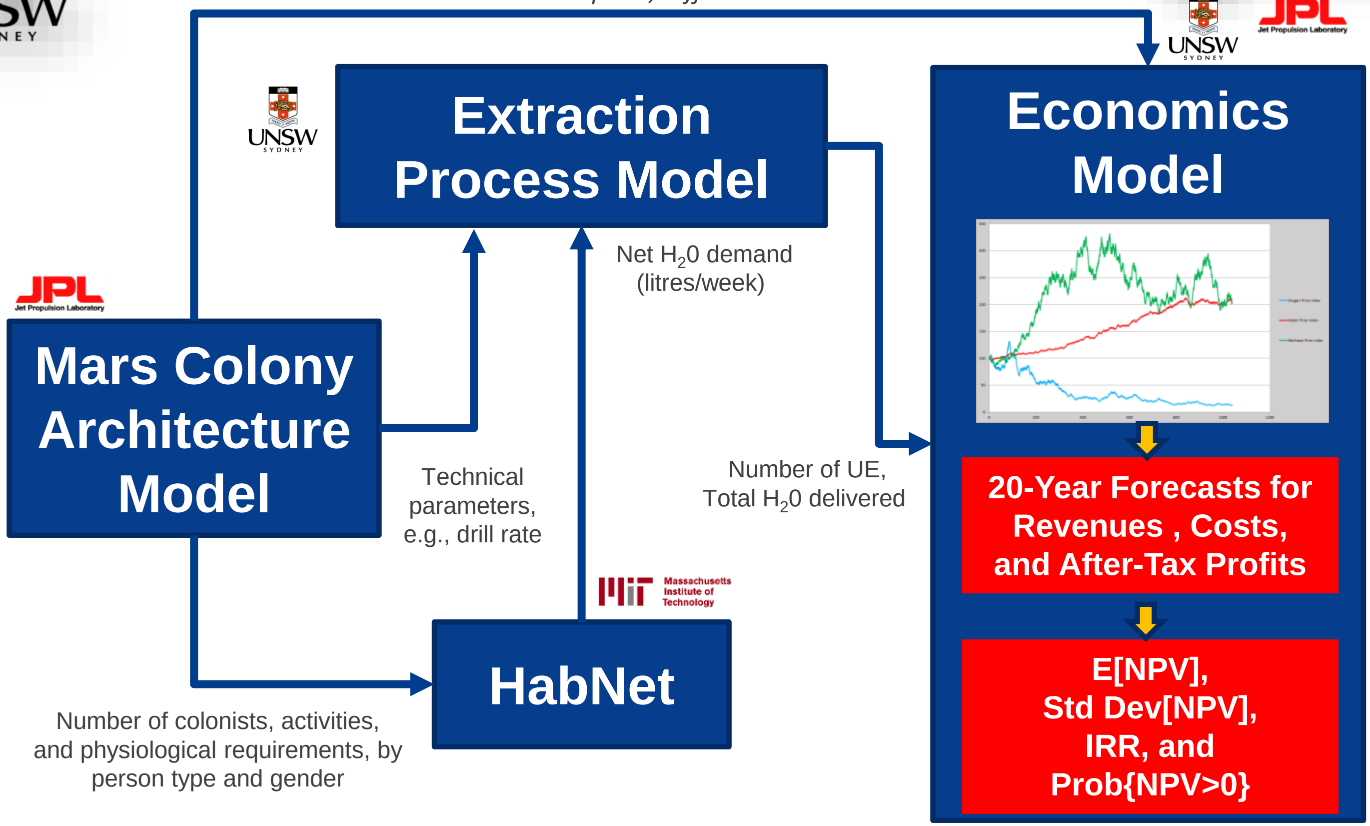
Source: S Casanova

Off-Earth Mining Research @ UNSW

- Initiated through
  - 2008, 2011, 2015 Int’l Future Mining Conference Series
  - 2013, 2015, 2017 Off-Earth Mining Forum Series
- *An Integrated Economics Model for ISRU in Support of A Mars Colony with JPL.*
- UNSW invested $50k to purchase a seismic recording system which is used at JPL.
- *Comprehensive Modelling for Off-Earth Mining Optimization and Resource Processing – Phase 1 with Ascentech, KSC, Virginia Tech.*
- UNSW has an agreement with JPL/NASA – A PhD student has 1-Year exchange opportunity in JPL every year.
- *Luxembourg Government - iSpace –*

AN INTEGRATED ECONOMICS MODEL FOR *IN-SITU* RESOURCE UTILISATION (ISRU) IN SUPPORT OF A MARS COLONY

Robert Shishko, Rene Fradet, Sydney Do, Serkan Saydam, Carlos Tapia Cortez, Andrew Dempster, Jeff Coulton

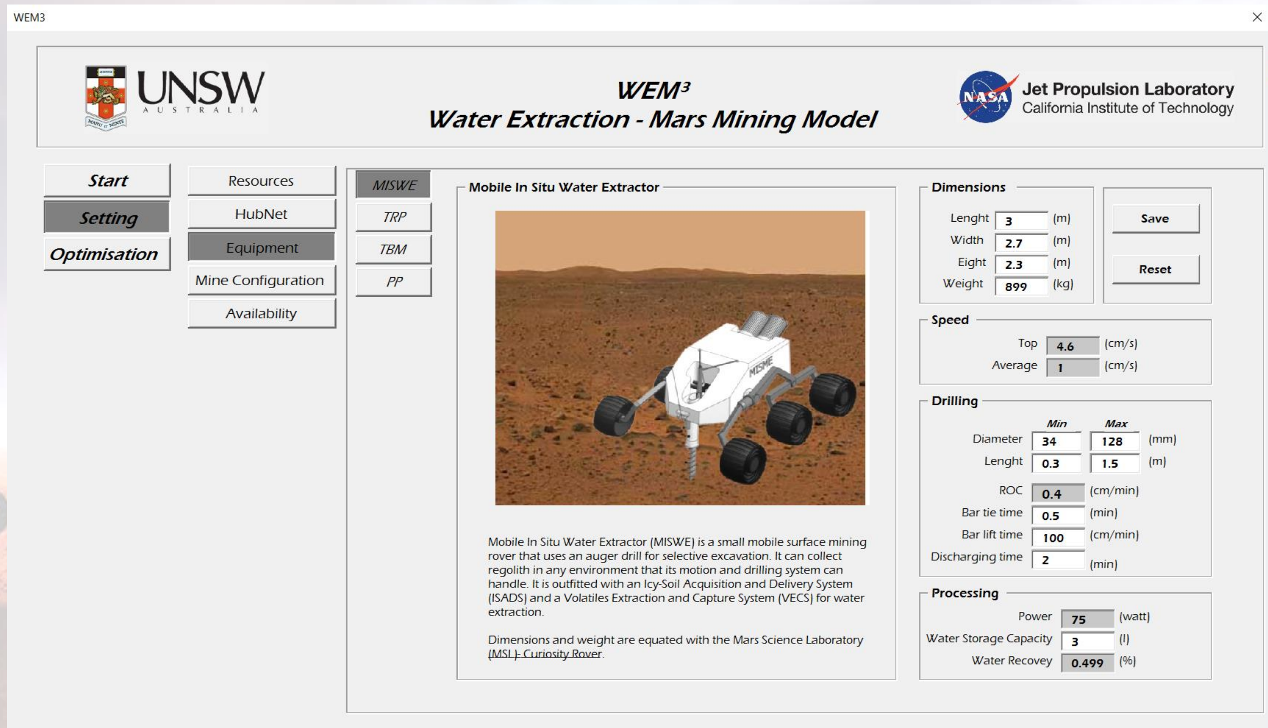


UE = Unit Equipment; NPV = Net Present Value; IRR = Internal Rate of Return

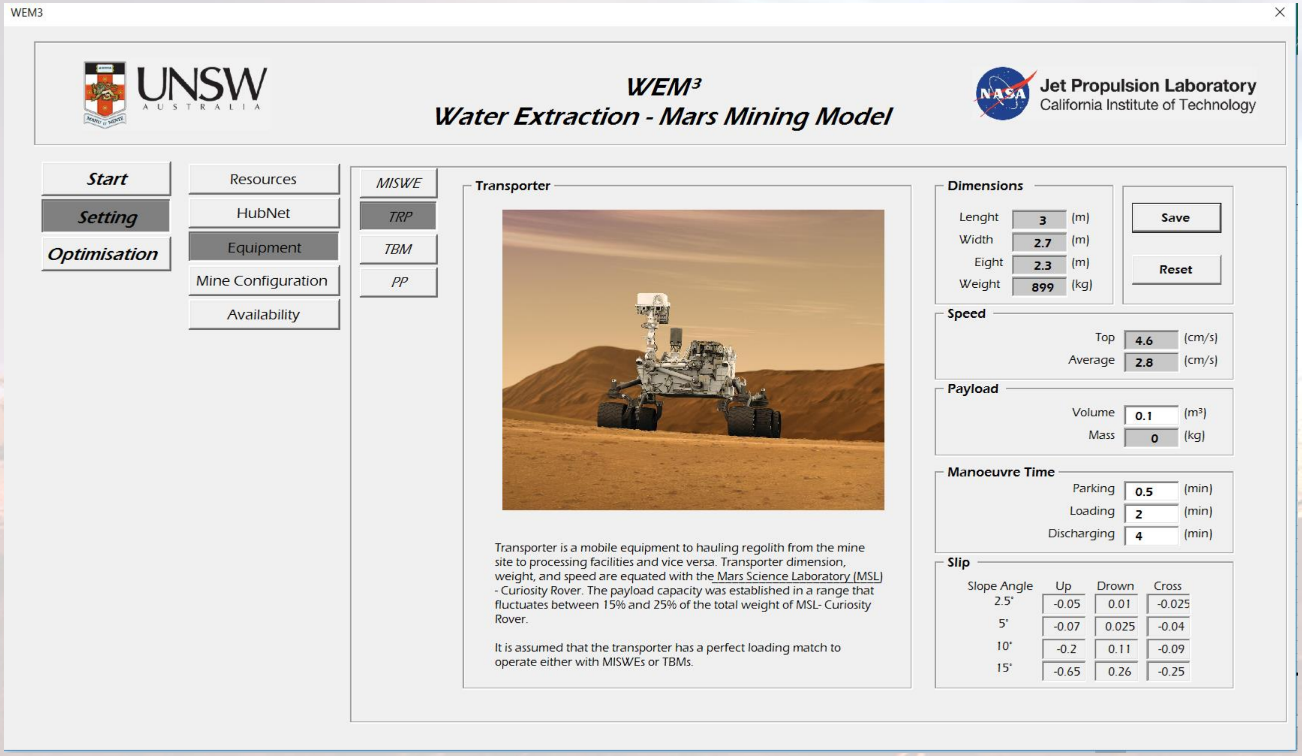
WEM^3

Simulates, optimises and assess the performance of Martian mining operations from a conceptual engineering point of view.

Works based on the open pit mining production and fleet optimisation techniques.



WEM³ Configuration – Equipment Setting



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journal homepage: www.elsevier.com/locate/actaastro

Mars Colony *in situ* resource utilization: An integrated architecture and economics model

Robert Shishko Principal Systems Engineer/Economist, Project Systems Engineering & Formulation Section [a,*], René Fradet Director, Engineering and Science Directorate [a], Sydney Do Systems Engineer, Project Systems Engineering & Formulation Section [a], Serkan Saydam Associate Professor and Research Director, School of Mining Engineering [b], Carlos Tapia-Cortez, Ph.D. Graduate Student [b], Andrew G. Dempster Director, Australian Centre for Space Engineering Research (ACSER) [c], Jeff Coulton Senior Lecturer [d]

[a] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109, USA*
[b] *School of Mining Engineering, UNSW, Sydney, 2052, Australia*
[c] *Australian Centre for Space Engineering Research, UNSW, Sydney, 2052, Australia*
[d] *UNSW Business School, University of New South Wales, Sydney, 2052, Australia*

A B S T R A C T

This paper reports on our effort to develop an ensemble of specialized models to explore the commercial potential of mining water/ice on Mars in support of a Mars Colony. This ensemble starts with a formal systems architecting framework to describe a Mars Colony and capture its artifacts' parameters and technical attributes. The resulting database is then linked to a variety of "downstream" analytic models. In particular, we integrated an extraction process (i.e., "mining") model, a simulation of the colony's environmental control and life support infrastructure known as HabNet, and a risk-based economics model. The mining model focuses on the technologies associated with *in situ* resource extraction, processing, storage and handling, and delivery. This model computes the production rate as a function of the systems' technical parameters and the local Mars environment. HabNet simulates the fundamental sustainability relationships associated with establishing and maintaining the colony's population. The economics model brings together market information, investment and operating costs, along with measures of market uncertainty and Monte Carlo techniques, with the objective of determining the profitability of commercial water/ice *in situ* mining operations. All told, over 50 market and technical parameters can be varied in order to address "what-if" questions, including colony location.

WEM³ is available on:
https://www.engineering.unsw.edu.au/mining-engineering/wem3

Comprehensive Modelling for Off-Earth Mining Optimization and Resource Processing M^2O^2

S Saydam, C Tapia Cortez (UNSW); L Sibille, Ascentech & KSC (NASA);
M Karmis, S Schafrik, M Karfakis, Aaron Noble (VTech)

- An SBIR – STTR grant – Phase 1, collaboratively achieved with UNSW, Virginia Tech, Ascentech and Kennedy Space Centre.
- The project applied our previous project outcomes to develop a comprehensive model for optimizing a mining operation to support a crew of max 10 people.

M^2O^2

Simulates Martian mining operation for regolith extraction and water production.

Assesses and compares technical requirements of Martian mining missions.

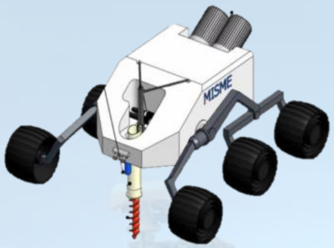
Uses geological, mineralogical and topographical data.

NASA (2017)
https://www.nasa.gov/feature/langley/university-students-mine-for-water-at-nasa-s-mars-ice-challeng

Off Earth Mining Technology

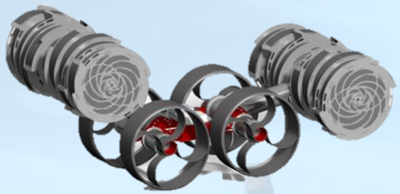
MISWE

HONEYBEE ROBOTICS



Rassor

SWAMP WORKS
NASA KENNEDY SPACE CENTER

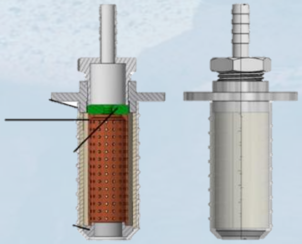


Rover/ Transporter

NASA

Corer

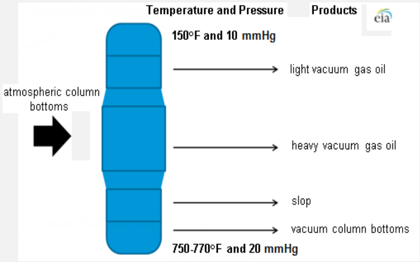
HONEYBEE ROBOTICS



Prospective

TBM

Vacuum Distillation



“Wilde”

January 2019: Wilde

Shadowed craters of the moon

“To reduce the risk perceived by a potential investor in a space resources venture”

Missions: Orbiter, Lander/Rover