Astro-1 Honors 2020
Class 4: Providing Power for Lunar Operations

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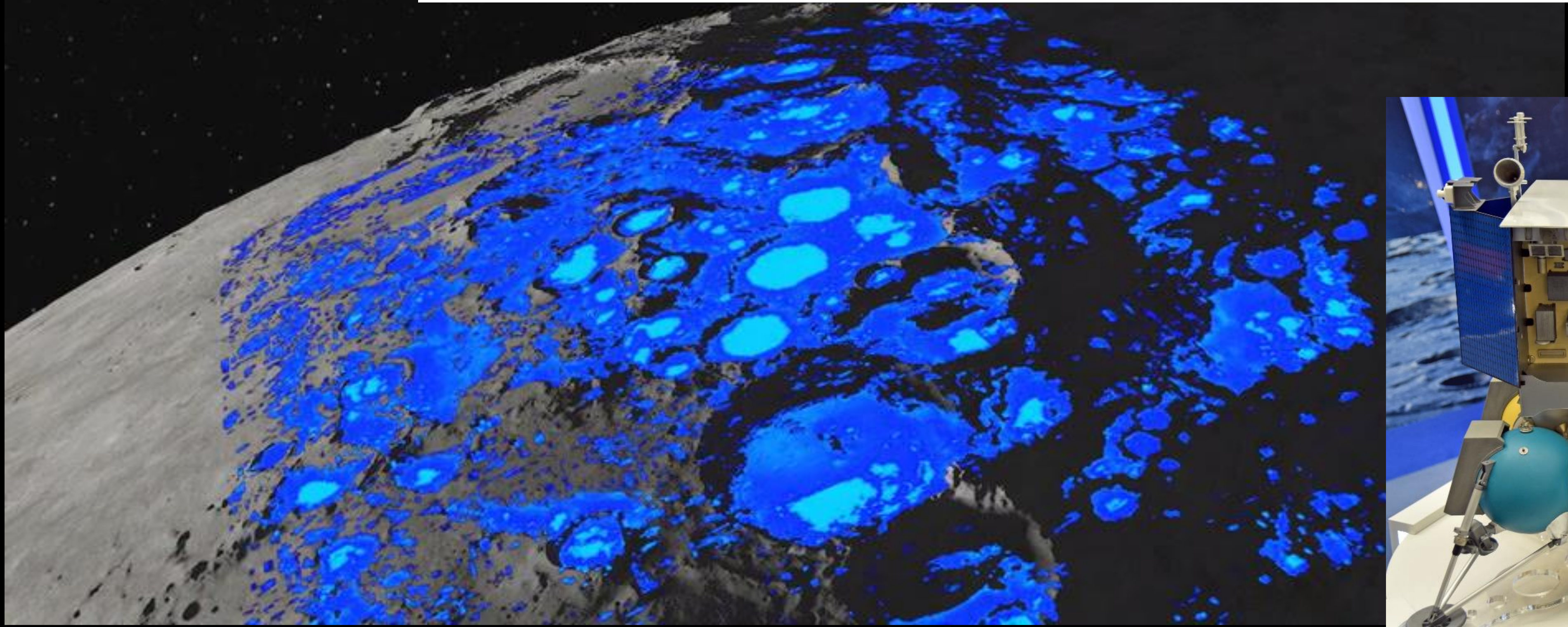
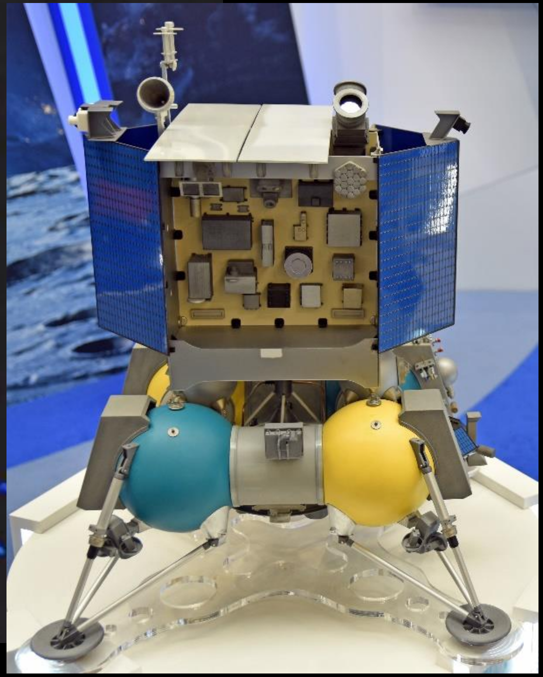
In the news this week!

SpaceRef Newsletter for Feb. 3rd: ESA will partner with the Russian Academy of Space Sciences' Luna-27 Mission to land a robotic drill and miniature laboratory at the Lunar South Pole to penetrate down to 1 meter, get samples, and analyze them on board the robotic lab named "PROSPECT."

https://exploration.esa.int/web/moon/-/59102-about-prospect





Luna-Resurs Mission scheduled for 2023-2024

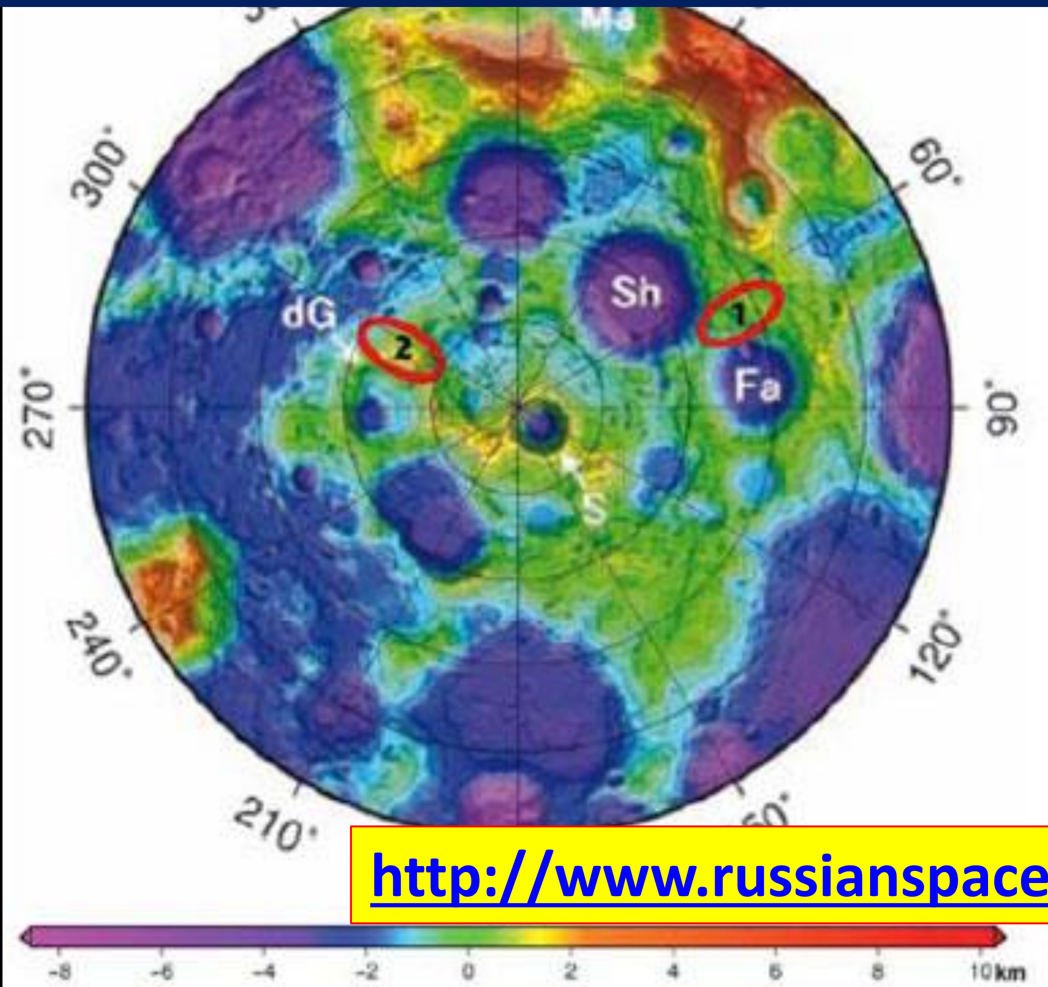


Figure 1. Topographic map of the South Pole of the Moon according to the Kaguya mision data [24]. The landing site #1 and #2 are shown by an ellipse of 15×30 km in size. dG – de Gerlache Crater, Sh - Shoemaker Crater , Fa - Faustini Crater S – Shackleton Crater.

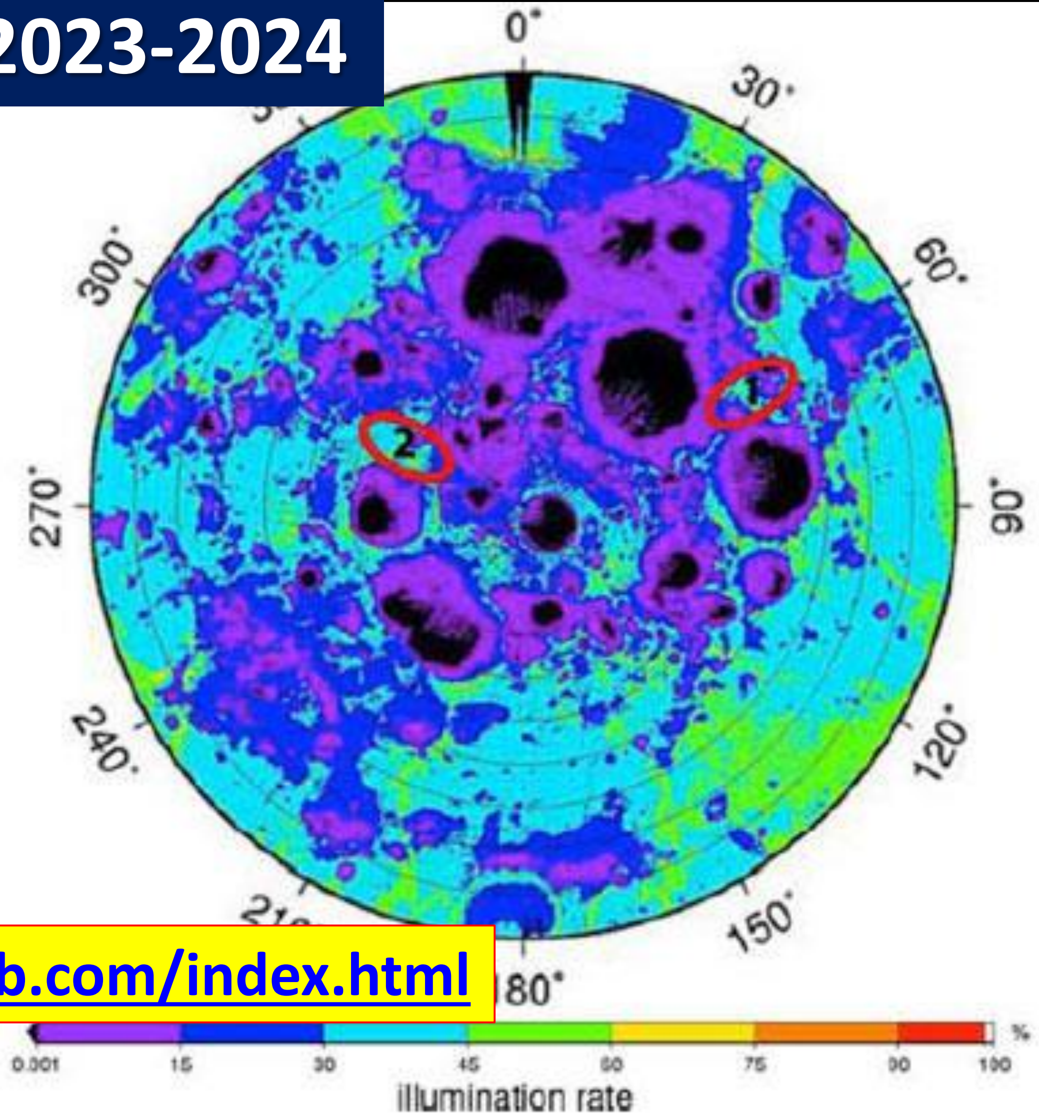


Figure 2. The illumination rate of the South Pole calculated for 2000 days [19]. The landing site #1 and #2 are shown by an ellipse of 15×30 km in size.

http://www.russianspaceweb.com/index.html

Potential Sources of Power for a Lunar Base

1. Solar power + thermal energy storage
2. Nuclear power
3. RTGs and Regenerative Fuel Cells
4. Directed Energy from orbit or Earth

Unit of power: Watts

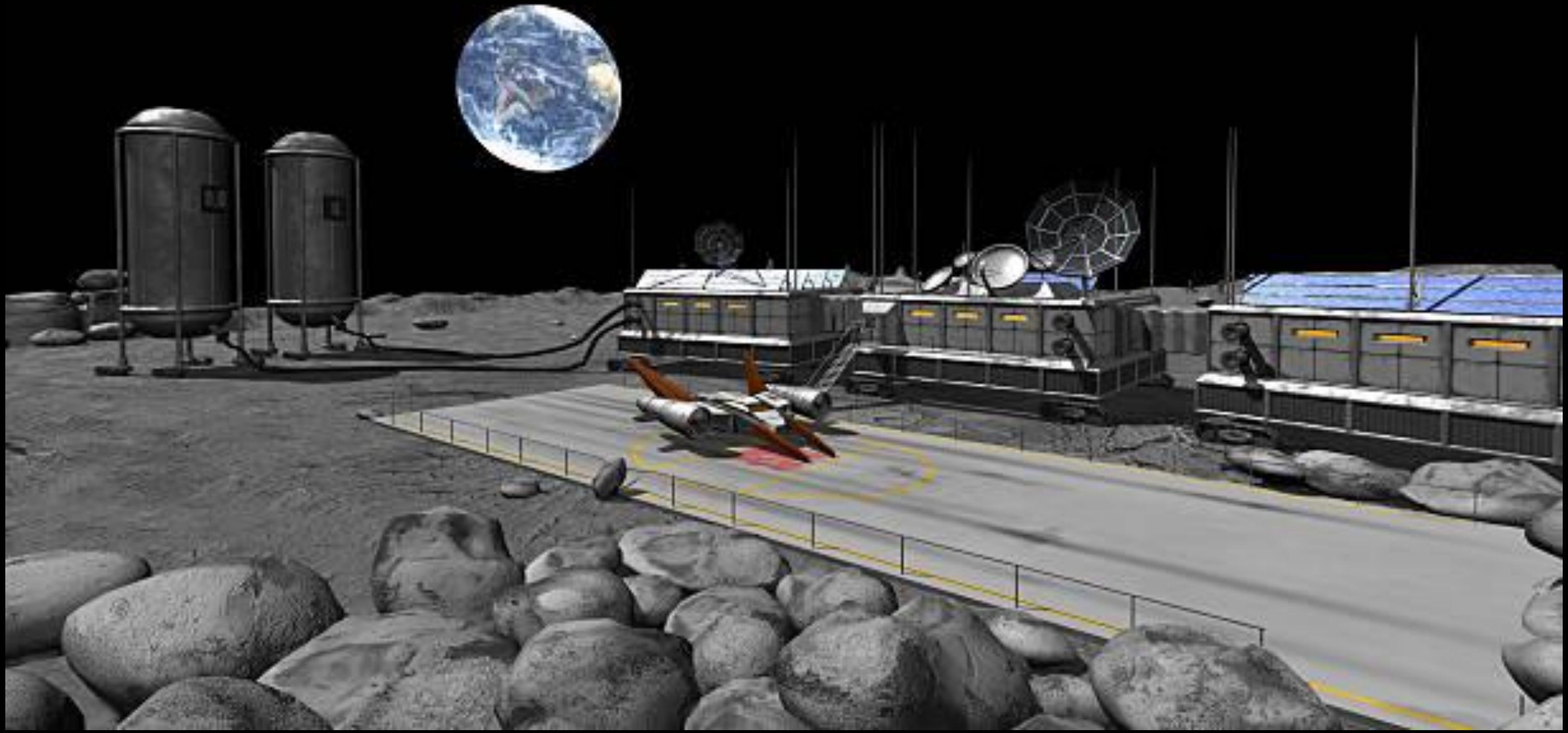
1 Watt = 1 Joule/second = Energy/time

ESA design of potential lunar settlement

Technology Readiness Levels Summary – Where are we with power generation for the Moon?

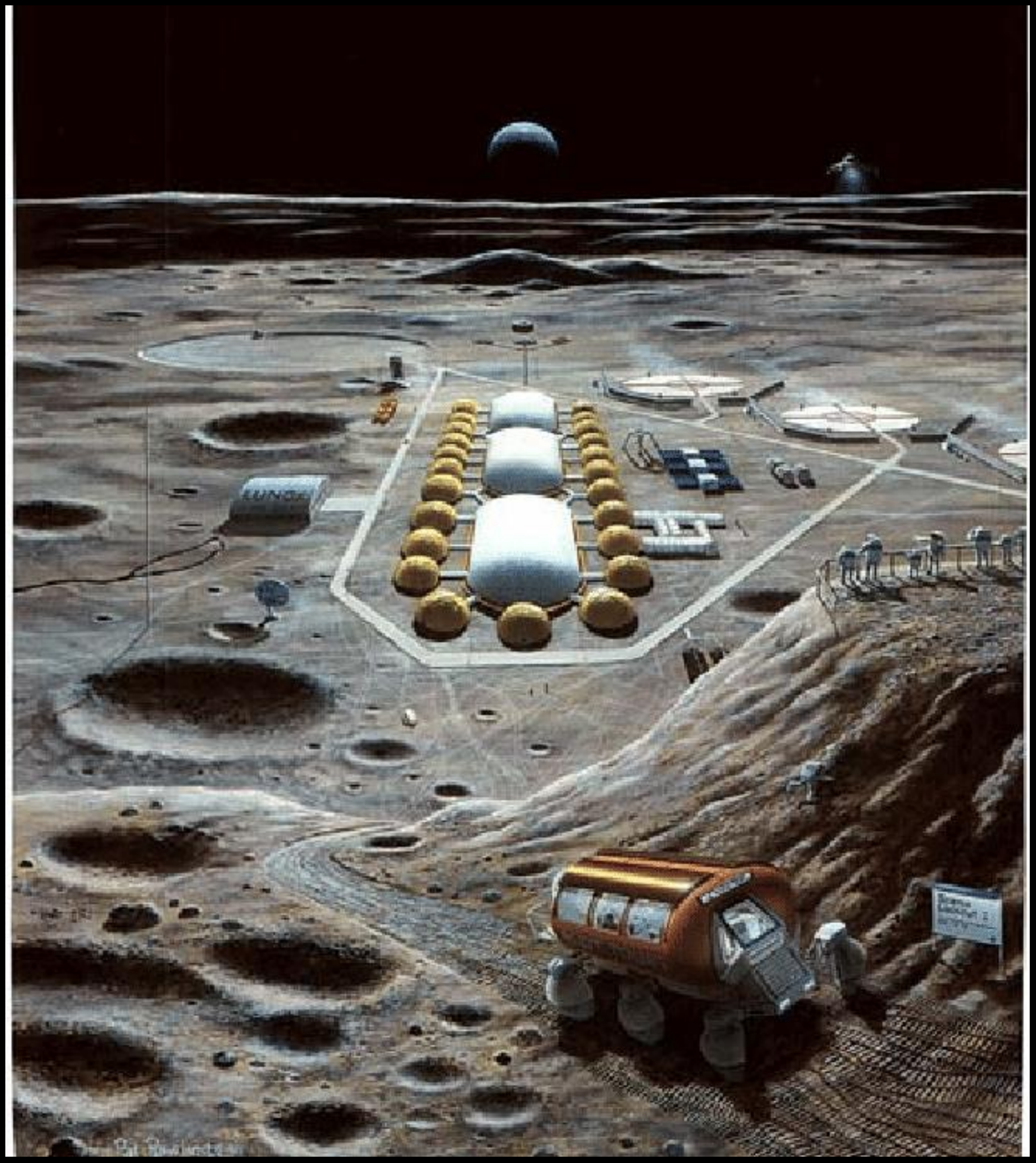
TRL 1 Basic principles understood
TRL 2 Technology concept and/or application formulated
TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept detailed
TRL 4 Component and/or breadboard validation in laboratory environment
TRL 5 Component and/or breadboard validation in relevant environment
TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7 System prototype demonstration in a space environment
TRL 8 Actual system completed and "flight qualified" through test and demonstration (ground and space)
TRL 9 Actual system "flight proven" through successful mission operations

What are the power needs for a lunar base?



Lunar Base Phased Construction

- Phase 0—Robotic Site Preparation (minimum or no human presence)
- Phase 1—Deployment and initial operations (3 to 4 personnel for 4 to 6 months)
- Phase 2—Growth Phase (approximately 10 personnel for a year)
- Phase 3—Self Sufficiency (ten to 100 personnel for extended periods)
- Phase 4—Science and Commercial (greater than 100 personnel for unlimited durations) (NASA study, 2006)



ESTIMATED ARRAY PEAK POWER REQUIREMENTS FOR PHASE-0

Loads	Phase 0 kWe
ISRU mining (Blair, 2005)	43
General Science (Cataldo and Bozek, 1993)	1
Rover Recharging (Catadalo and Bozek, 1993)	5
RFC Parasitic Load	25
10 percent margin	7
Total	81

Need to provide power during lunar day, store power to distribute for operations during lunar night.

For reference, here are recordings of talks at a conference in 2018 about surviving the lunar night:
https://www.hou.usra.edu/meetings/survivethenight2018/program/program-recordings.pdf

In deciding on how to generate power for lunar settlements, keep in mind:

One lunar day = ~27 Earth days = the time it takes the Moon to rotate once on its axis.

The Moon's orbit is tilted only 1.5^0 to the plane of the ecliptic, so the Moon does not have seasons, and the poles receive more consistent sunlight than the equatorial regions.

One lunar day = One lunar year = the time for the Moon to orbit the Earth once.

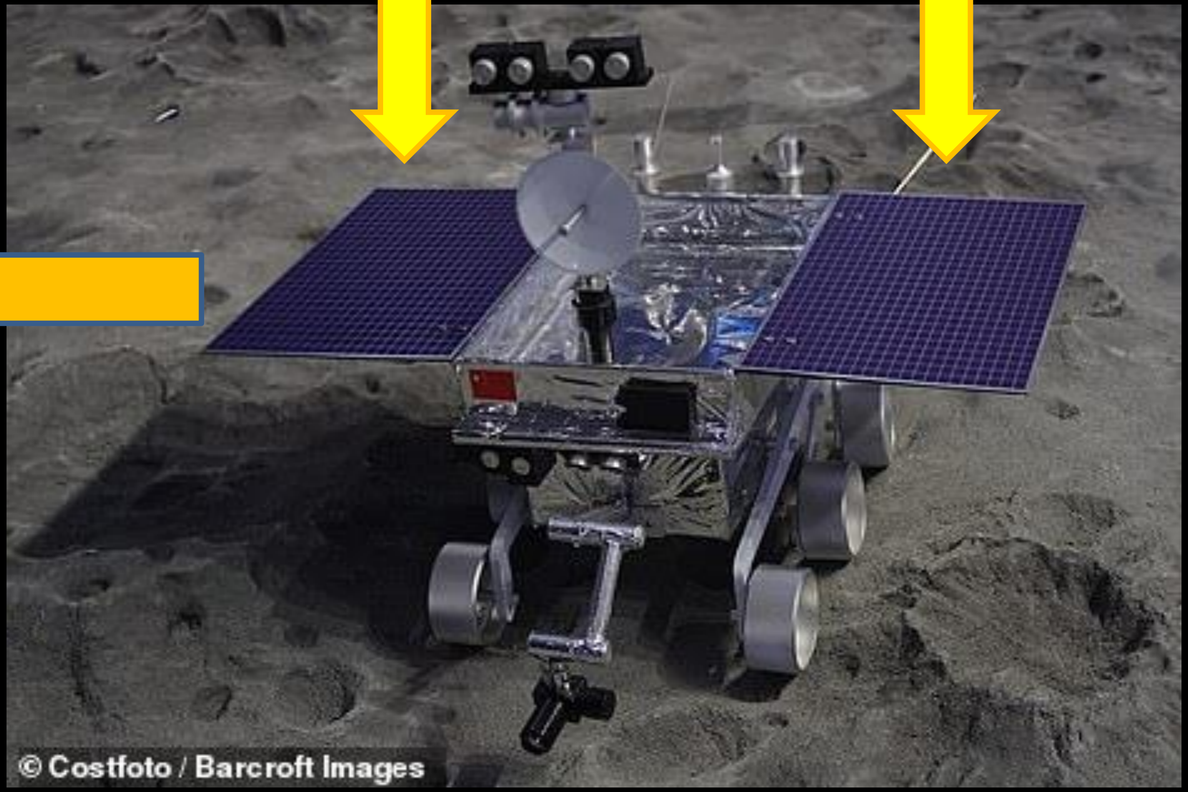
These are important concepts to keep in mind when considering how to generate power for human settlements on the Moon.

Solar Power

Average Solar illumination at 1 AU = 1360 Watts/m^2 = 1.36 x 10^3 W/m^2 or 1.36 kW/m^2

1360 Watts/m^2

25-30% efficiency output power for photovoltaic conversion ~ 340-400 Watts of power out



1360 Watts/m² from the Sun

THE PEAKS OF ETERNAL LIGHT ON THE LUNAR SOUTH POLE

How they were found and what they look like

Michiel Kruijff, Delta-Utec, +31 (71) 523 0662, www.delta-utec.com

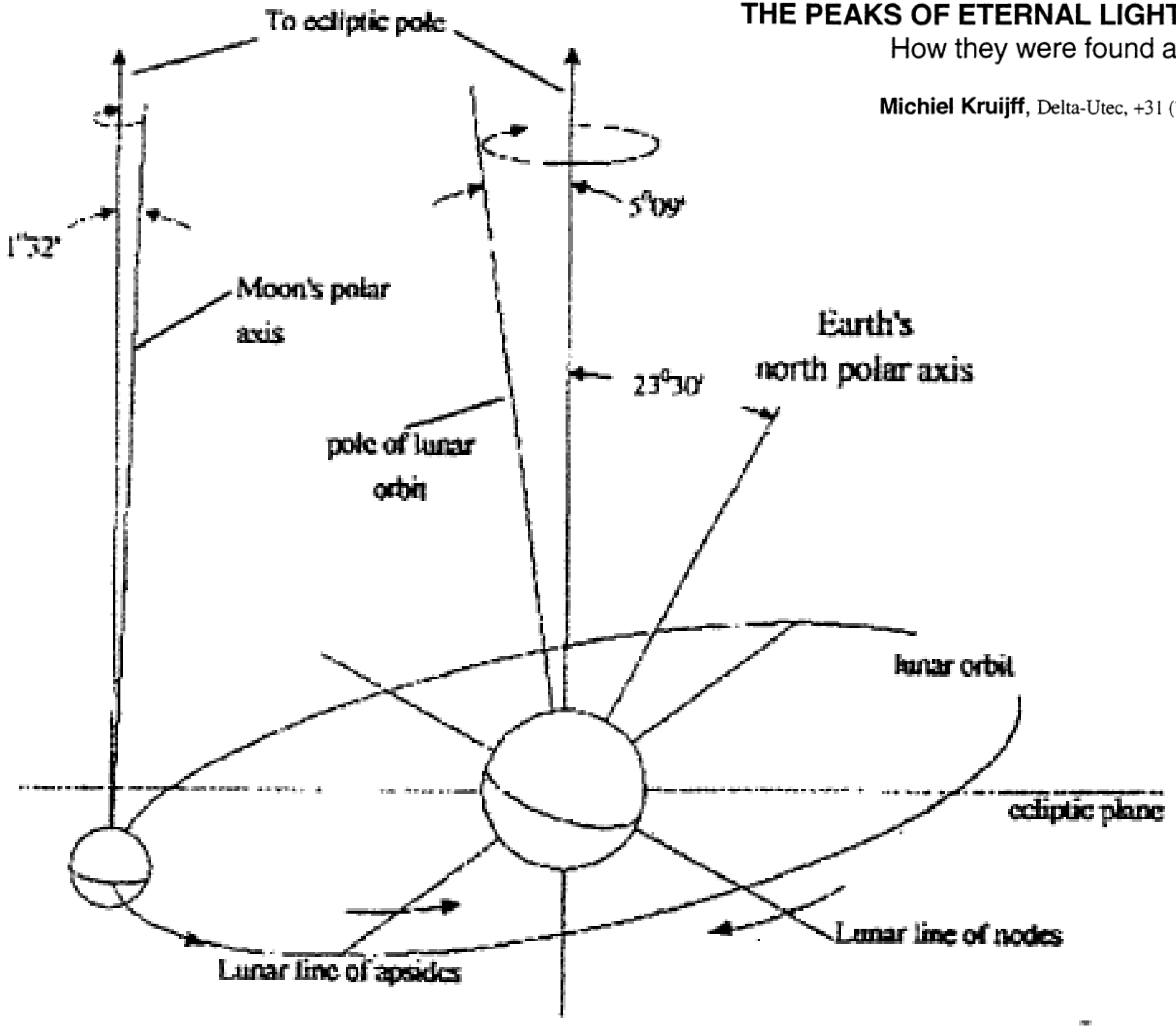
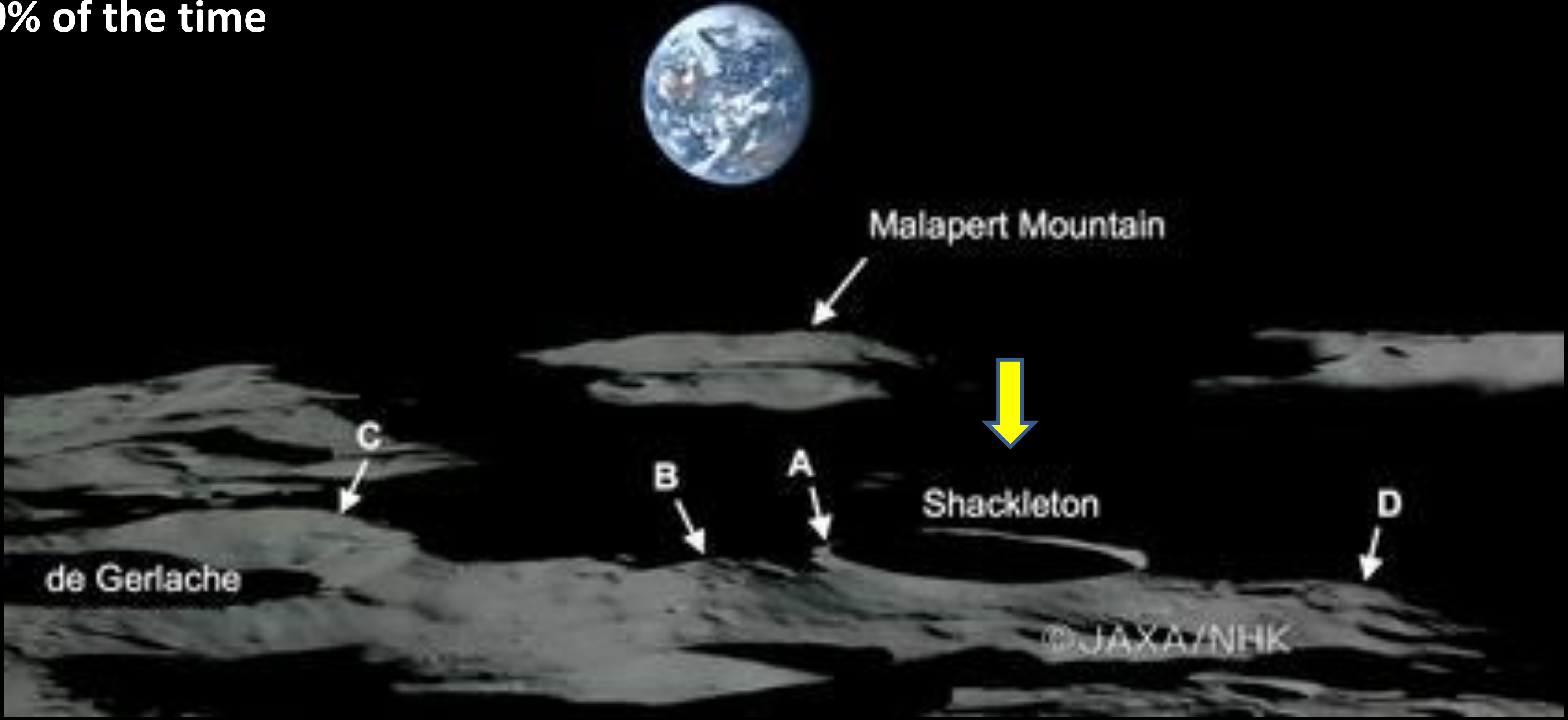


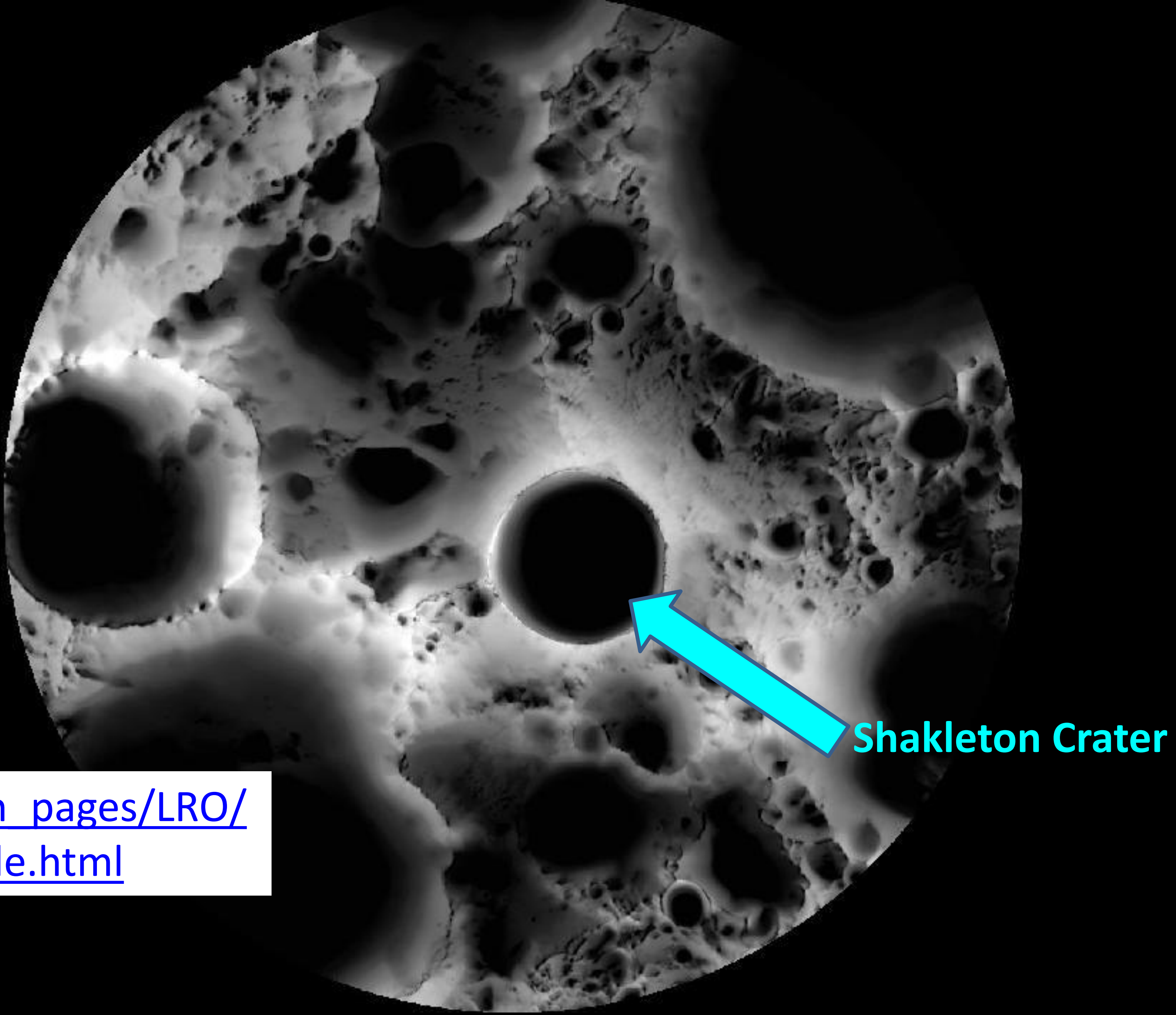
Fig. 1. Angles in the Earth-Moon system

“Peaks of Eternal Light” – hypothetical points on the surface of an astronomical body that are always in sunlight

At the Lunar South Pole 4 regions have been identified which are illuminated more than 80% of the time

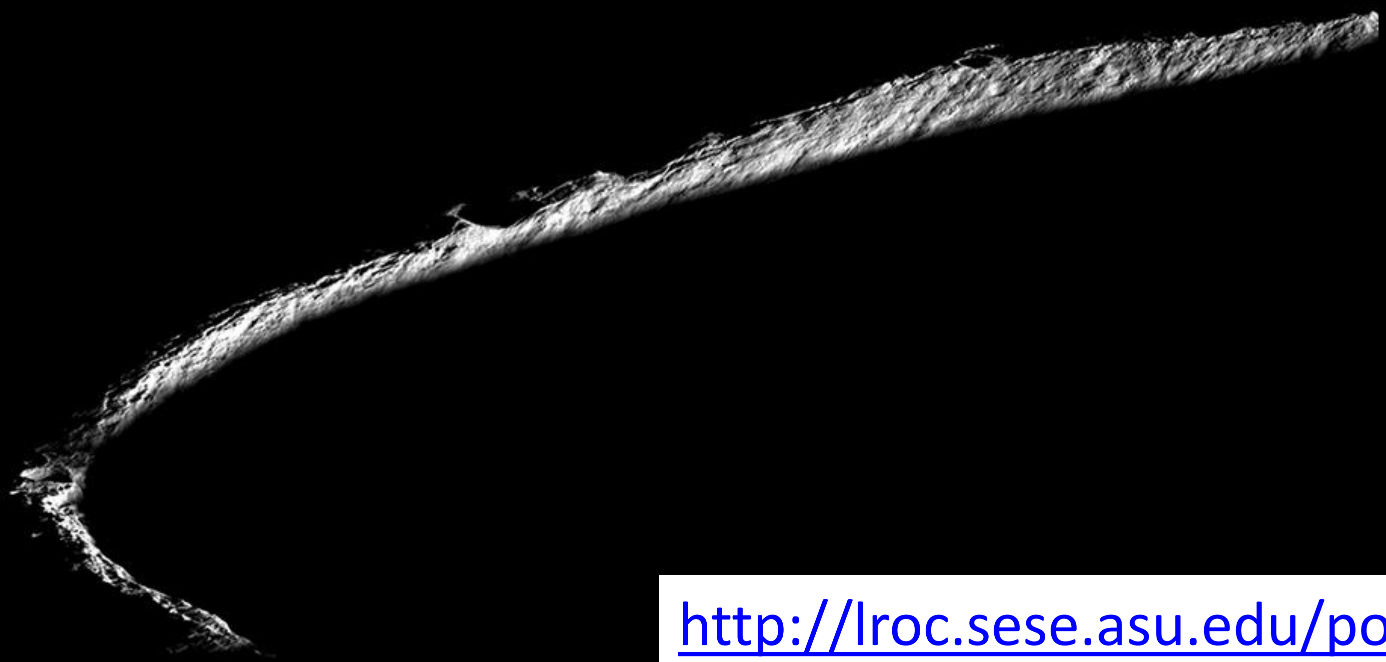


Six month composite image of the lunar south pole taken by the LRO camera showing average illumination over a six month period. Bright areas are the peak illumination regions which are in sunlight 80-90% of the time.



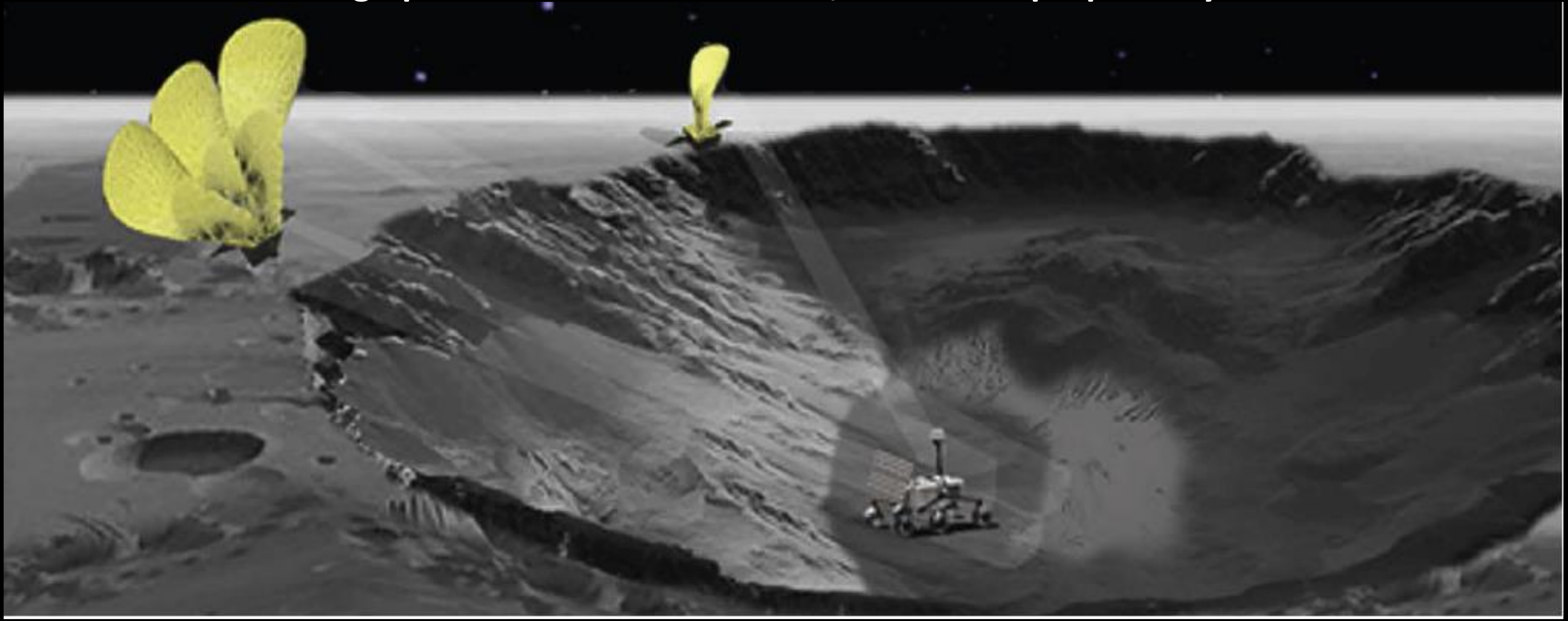
https://www.nasa.gov/mission_pages/LRO/multimedia/gallery/121510pole.html

Spectacular oblique view of the rim of Shackleton crater (21 km diameter, 89.66°S, 129.20°E). While no location on the Moon stays continuously illuminated, three points on the rim remain collectively sunlit for more than 90% of the year. These points are surrounded by topographic depressions that never receive sunlight, creating cold traps that can capture ices, NAC M1224655261LR [NASA/GSFC/Arizona State University].



http://lroc.sese.asu.edu/posts/993

Large unfolding solar panels collect light from the PEL at the rim of Shakleton Crater and illuminate mining operations inside the crater, where it is perpetually dark.

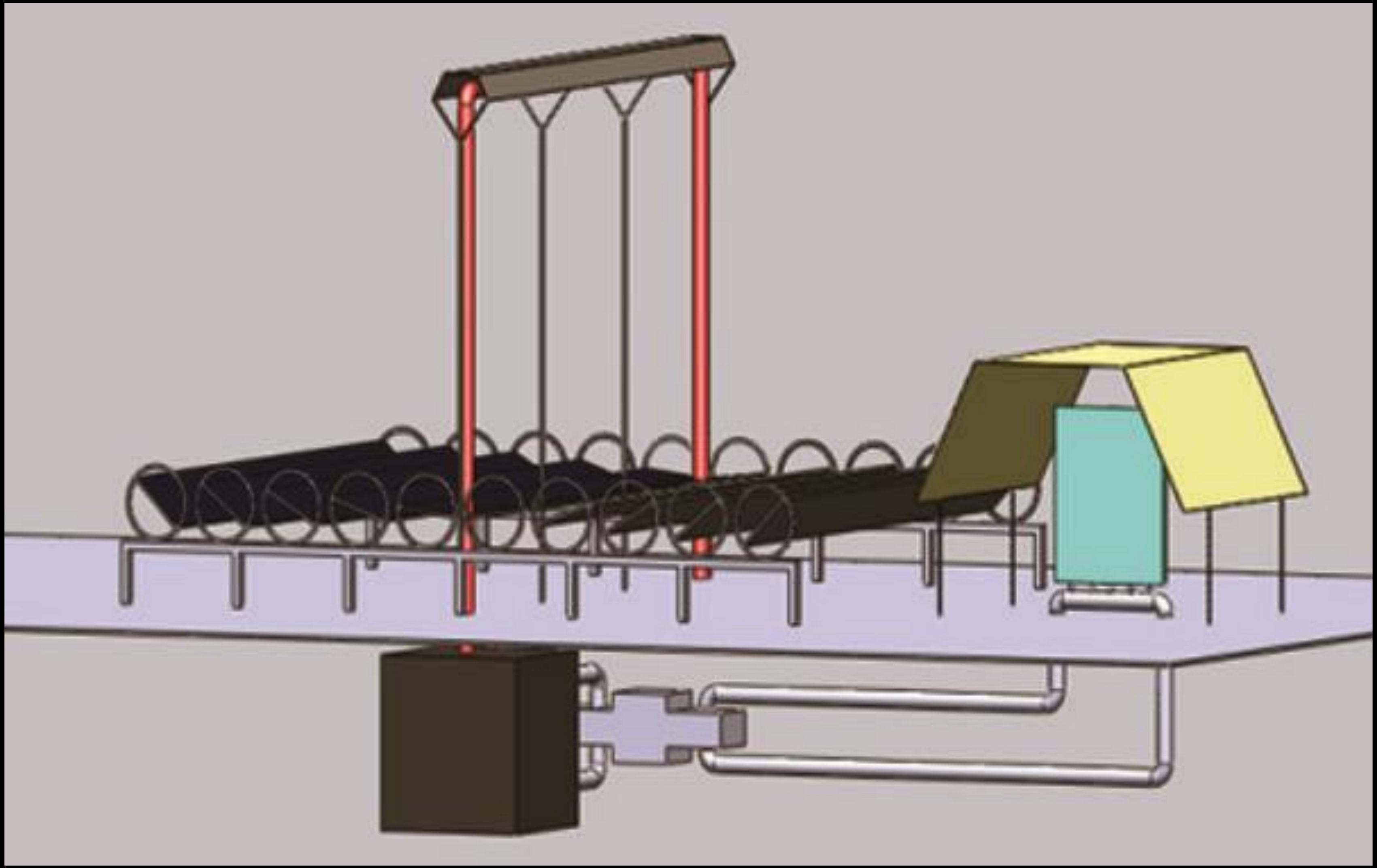


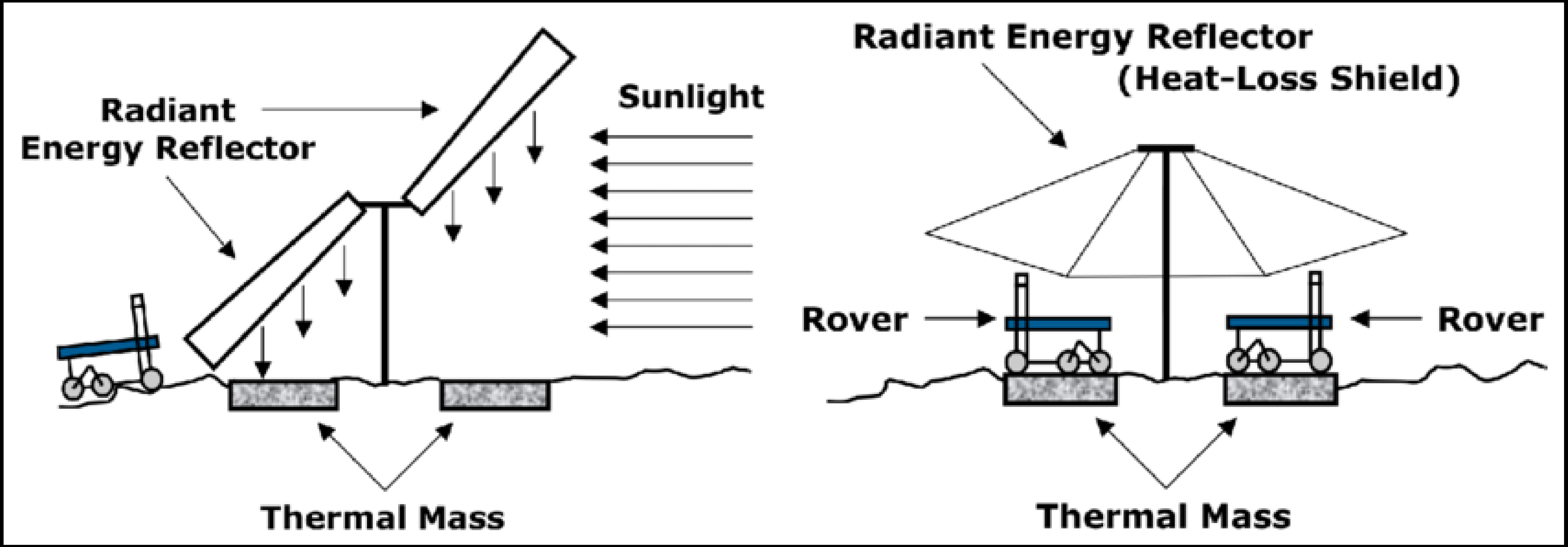
From: Transformers for Lunar Extreme Environments, NIAC study, JPL, 2017

Thermal energy: renewable resource on the Moon.
Heat bricks made from lunar regolith, insulate, during the lunar day (around 14 Earth days). Store the heat and slowly release it to provide energy via heat engines during the lunar night.

https://scienceillustrated.com.au/blog/science/powering-a-moon-base/

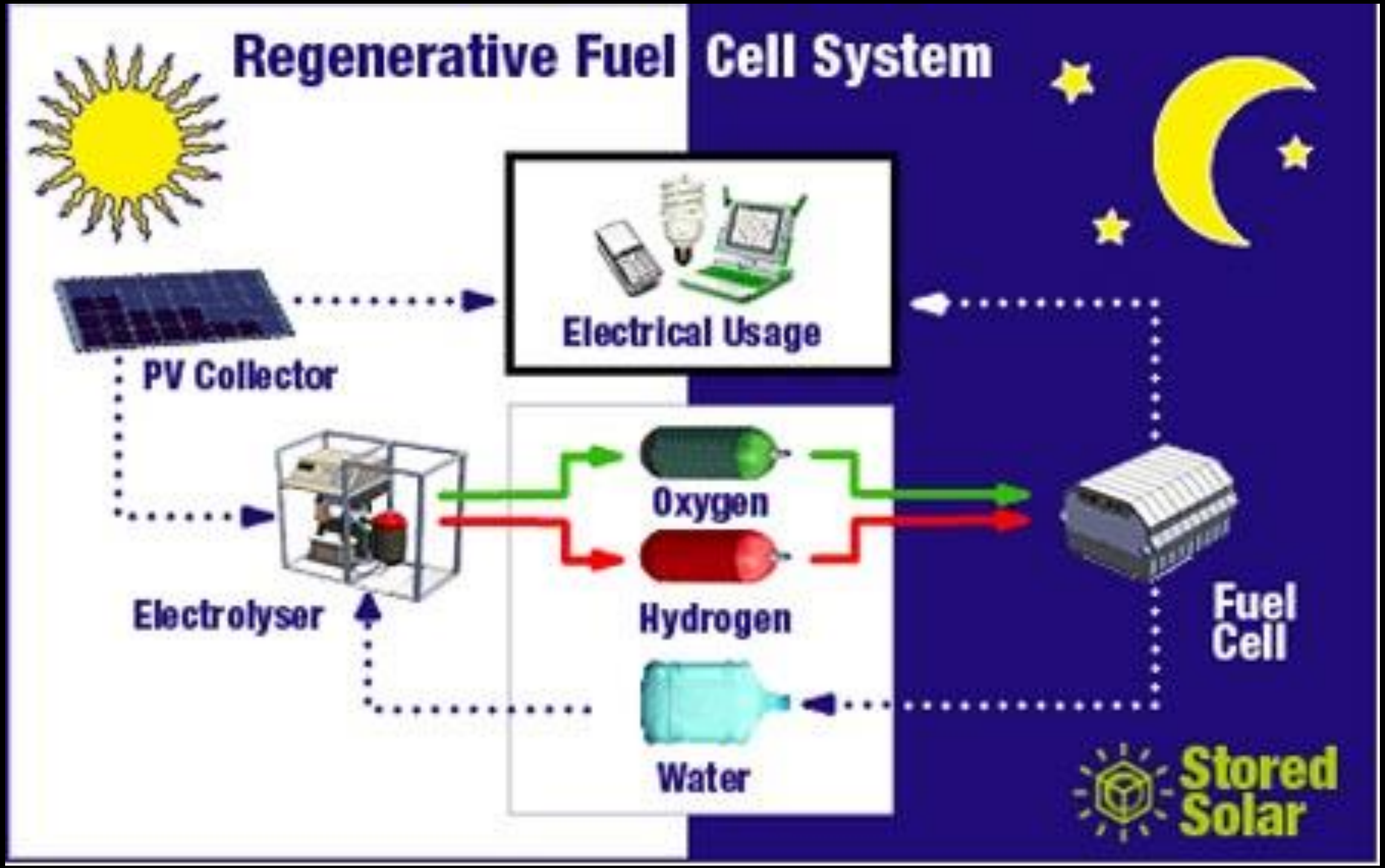
System for producing electricity on the Moon. Fresnel reflectors (dark blue and grey mirrors) will concentrate solar rays into the elongated collector above. Beneath, there is a tube filled with fluid that transforms into a gas when heated. This heats the thermal mass or reservoir (grey box), which can transfer it to a Stirling engine (cross-shaped object) to produce electricity. The radiator (green) can heat rovers and crew. The yellow cover prevents the heat from rapidly dissipating. / Blai Climent et al



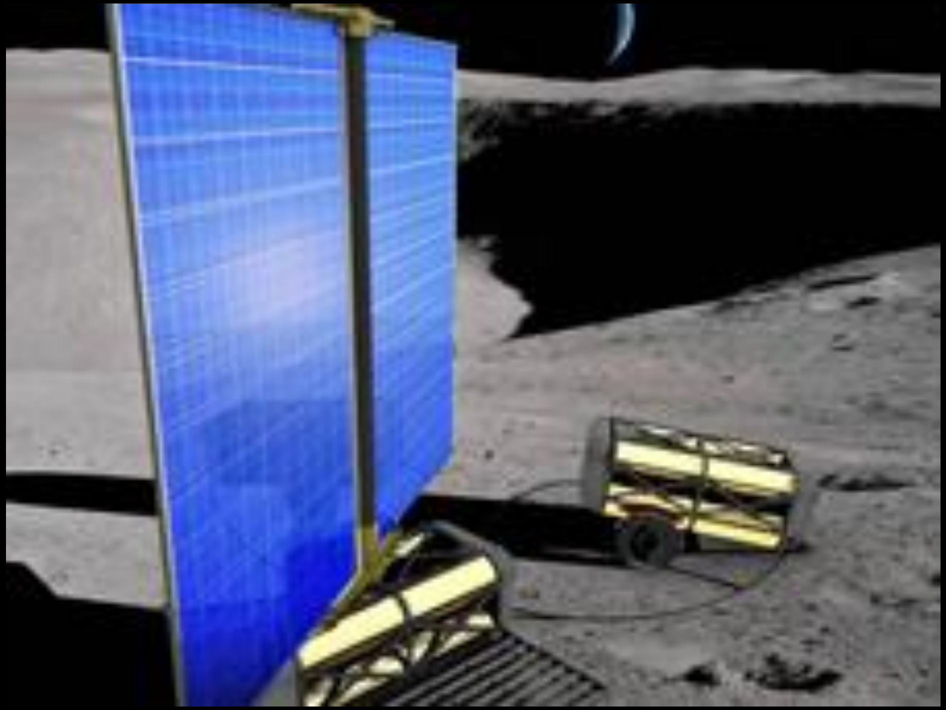


The Lunar Thermal Wadi Concept. On the left, a sun-tracking reflector directs sunlight onto a thermal mass during periods of solar illumination while rovers conduct lunar surface operations. On the right, rovers are thermally coupled to the thermal mass to stay warm during periods of darkness, and are further protected by a heat-loss shield to limit radiative losses to space.

Regenerative Fuel Cells



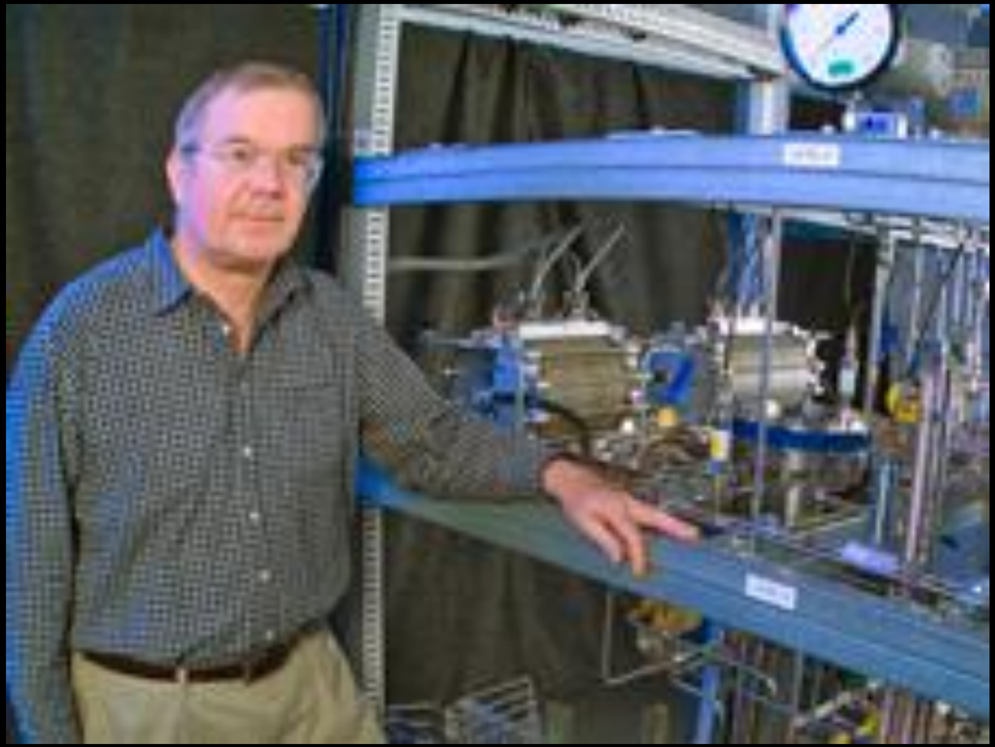
A regenerative fuel cell system collects solar energy during the day, stores energy, and releases it during the night.



"What makes our regenerative fuel cell unique is that it's closed loop and completely sealed," Bents said. "Nothing goes in and nothing comes out, other than electrical power and waste heat. The hydrogen, oxygen and product water inside are simply recycled over and over again."

Regenerative fuel cell stacks at NASA Glenn. Credit: NASA

https://www.nasa.gov/exploration/home/lunar_fuel_cell.html



NASA Glenn's David Bents with the first closed-loop regenerative fuel cell ever demonstrated. Credit: NASA

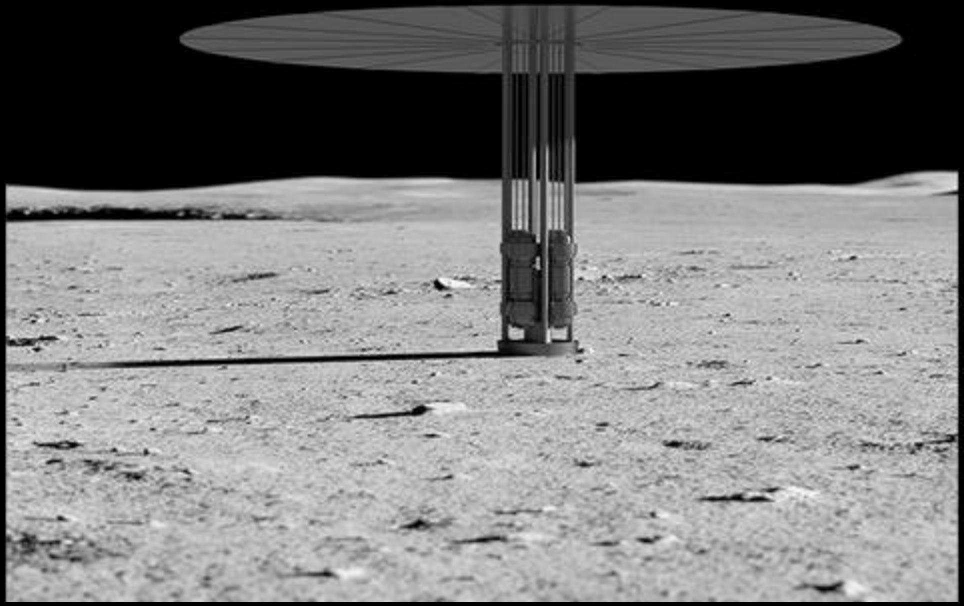
Nuclear Power

NASA is developing trashcan-sized nuclear reactors to provide steady power for a lunar colony. The presence of near-constant sunlight at some parts of the South Pole, like the Shackleton Crater, are great for solar power, but the first inhabitants will need a more reliable energy source, right away.

A solid block of uranium-235 nuclear fuel the size of a paper-towel roll will generate heat to boil sodium at 1,600°F inside eight tubes, which will transfer energy to a Stirling engine to turn heat into electricity.

https://www.popularmechanics.com/space/moon-mars/a28364235/nasa-moonbase/

See also https://sservi.nasa.gov/articles/a-lunar-nuclear-reactor/



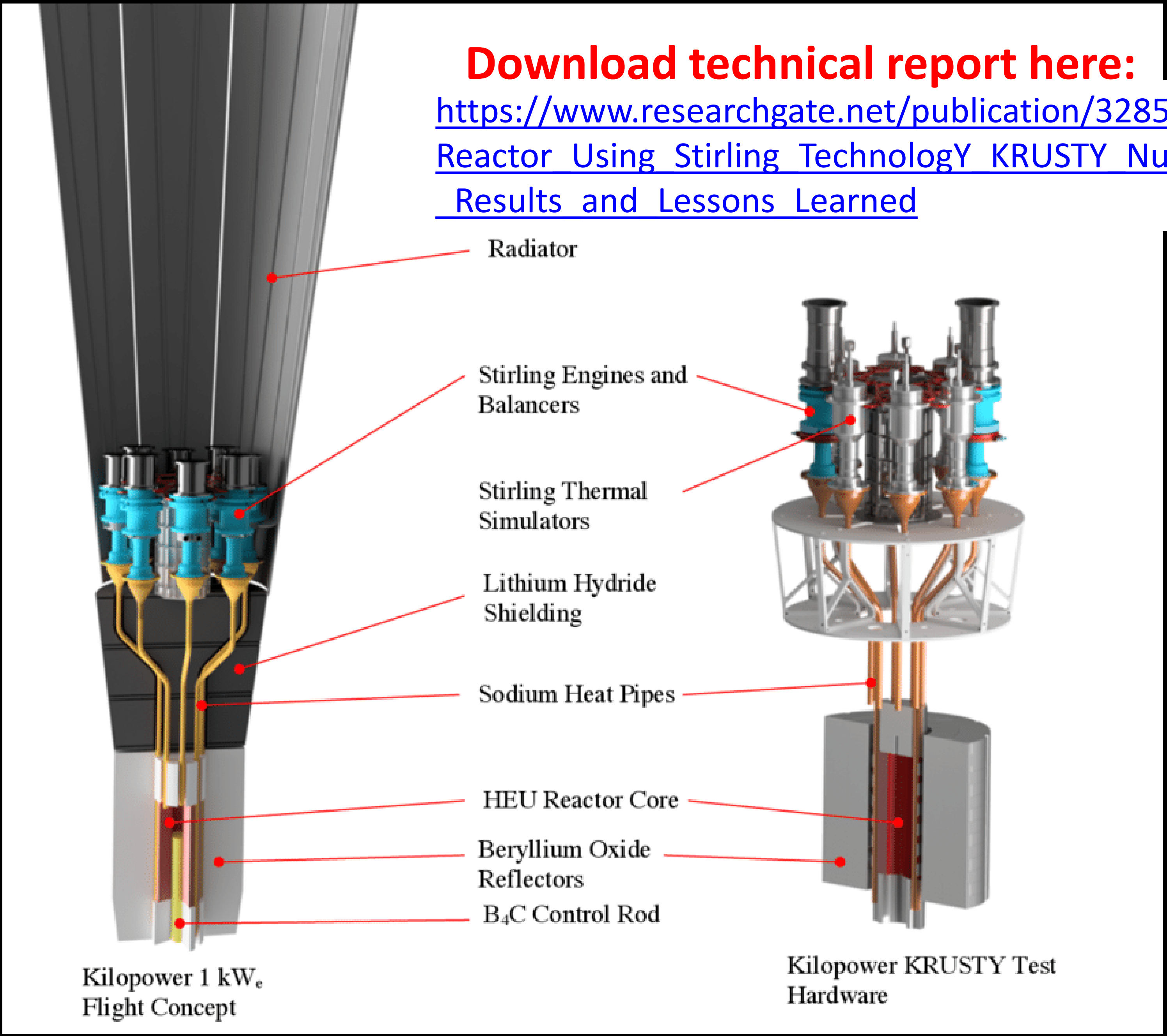
Nuclear Fission is one option, but it leaves a lot of radioactive waste.

If all goes as planned, sometime in the next decade an American robotic lander will arrive at a burgeoning moon base toting a small nuclear reactor. Inside the reactor a boron control rod will slide into a pile of uranium and start a nuclear chain reaction, splitting uranium atoms apart and releasing heat. Next that warmth will be piped to a generator. Then the lights will come on—and stay on, even through long, cold lunar nights.

https://www.scientificamerican.com/article/will-nasa-go-nuclear-to-return-to-the-moon/

Download technical report here:

https://www.researchgate.net/publication/328537980_Kilopower_Reactor_Using_Stirling_TechnologY_KRUSTY_Nuclear_Ground_Test_Results_and_Lessons_Learned



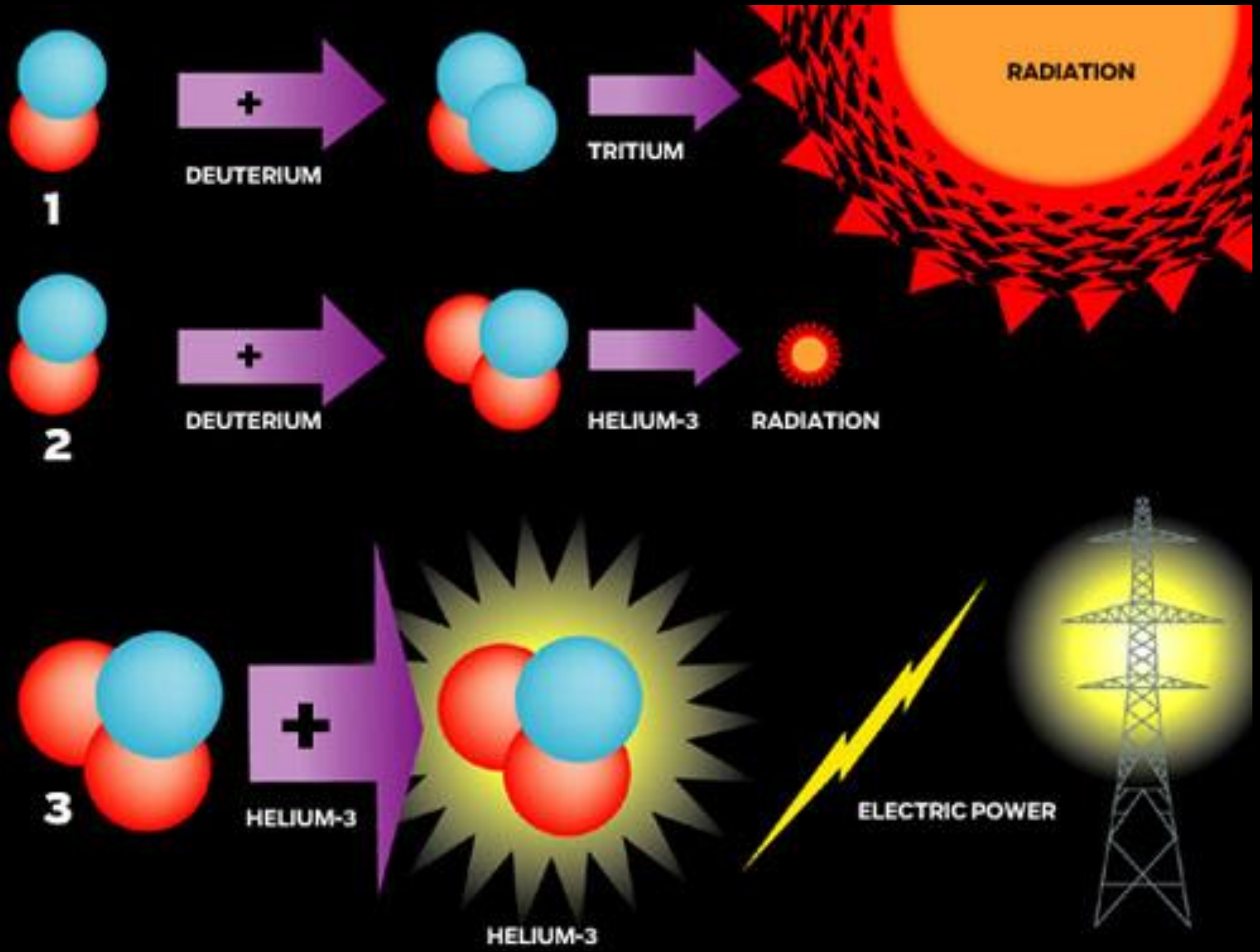
Kilopower 1 kW_e Flight Concept

Kilopower KRUSTY Test Hardware

What about nuclear fusion?

Nuclear fusion of helium-3 (^3He) can be used to generate electrical power with little or no radioactive waste and no carbon emissions. Although rare on Earth, an estimated one million tons of ^3He has collected on the surface of the moon.
https://journals.sagepub.com/doi/10.1177/1946756714536142

The discovery of a helium isotope, helium-3, on the moon has given scientists ideas on how to produce electricity far more efficiently than with hydrocarbons or current nuclear plants. The large amounts of energy would come without danger of releasing radioactive substances into the atmosphere.


RADIATION
1
DEUTERIUM
TRITIUM
2
DEUTERIUM
HELIUM-3
RADIATION
3
HELIUM-3
HELIUM-3
ELECTRIC POWER

Fusion Can be Conveniently Divided into Three Eras

1st Generation

$D + T \rightarrow n\ (14.07\ MeV) + {}^{4}He\ (3.52\ MeV)$

$D + D \rightarrow n\ (2.45\ MeV) + {}^{3}He\ (0.82\ MeV)$ {50%}

$\rightarrow p\ (3.02\ MeV) + T\ (1.01\ MeV)$ {50%}

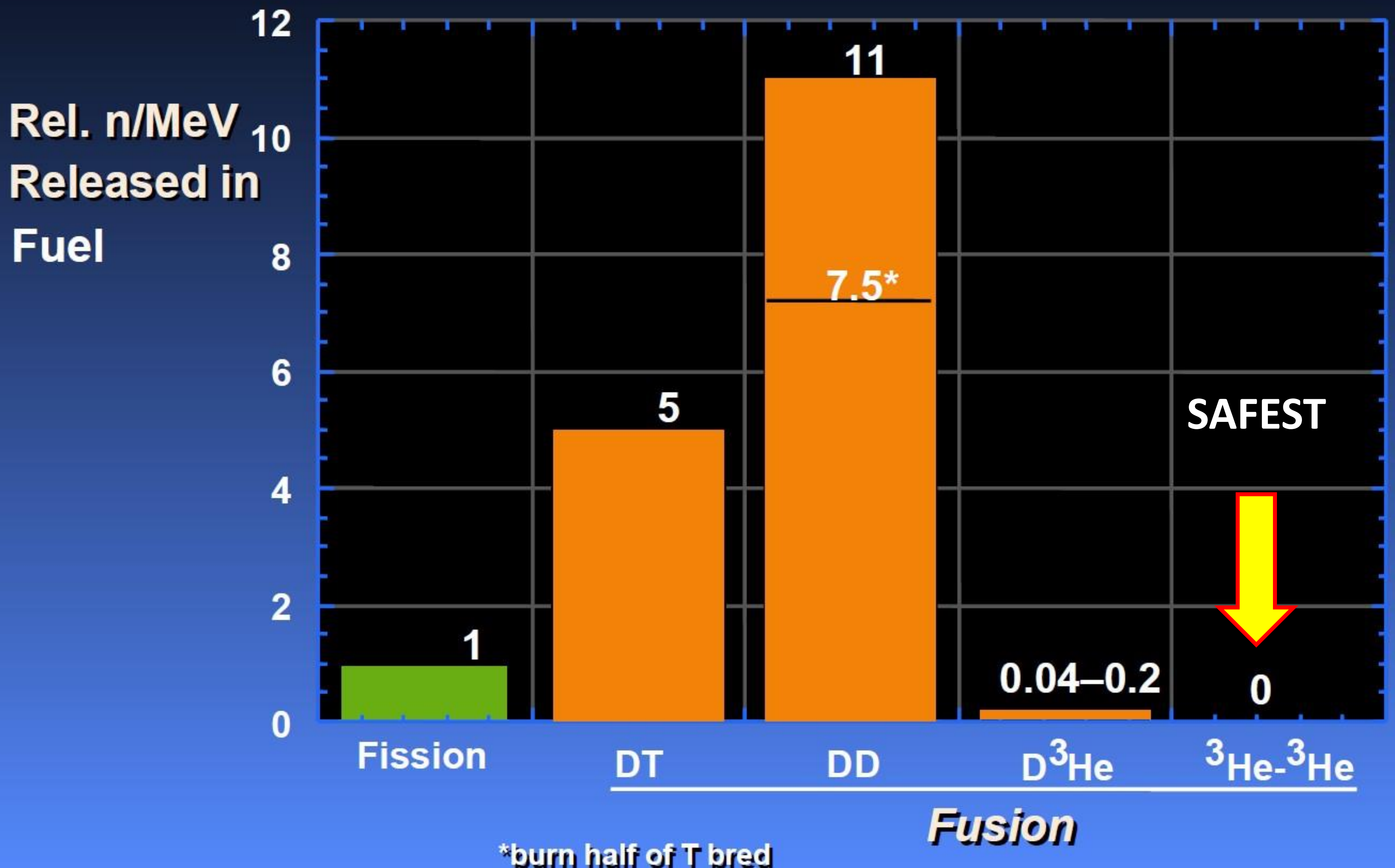
2nd Generation

$D + {}^{3}He \rightarrow p\ (14.68\ MeV) + {}^{4}He\ (3.67\ MeV)$

3rd Generation

${}^{3}He + {}^{3}He \rightarrow 2p + {}^{4}He$ (12.9 MeV)

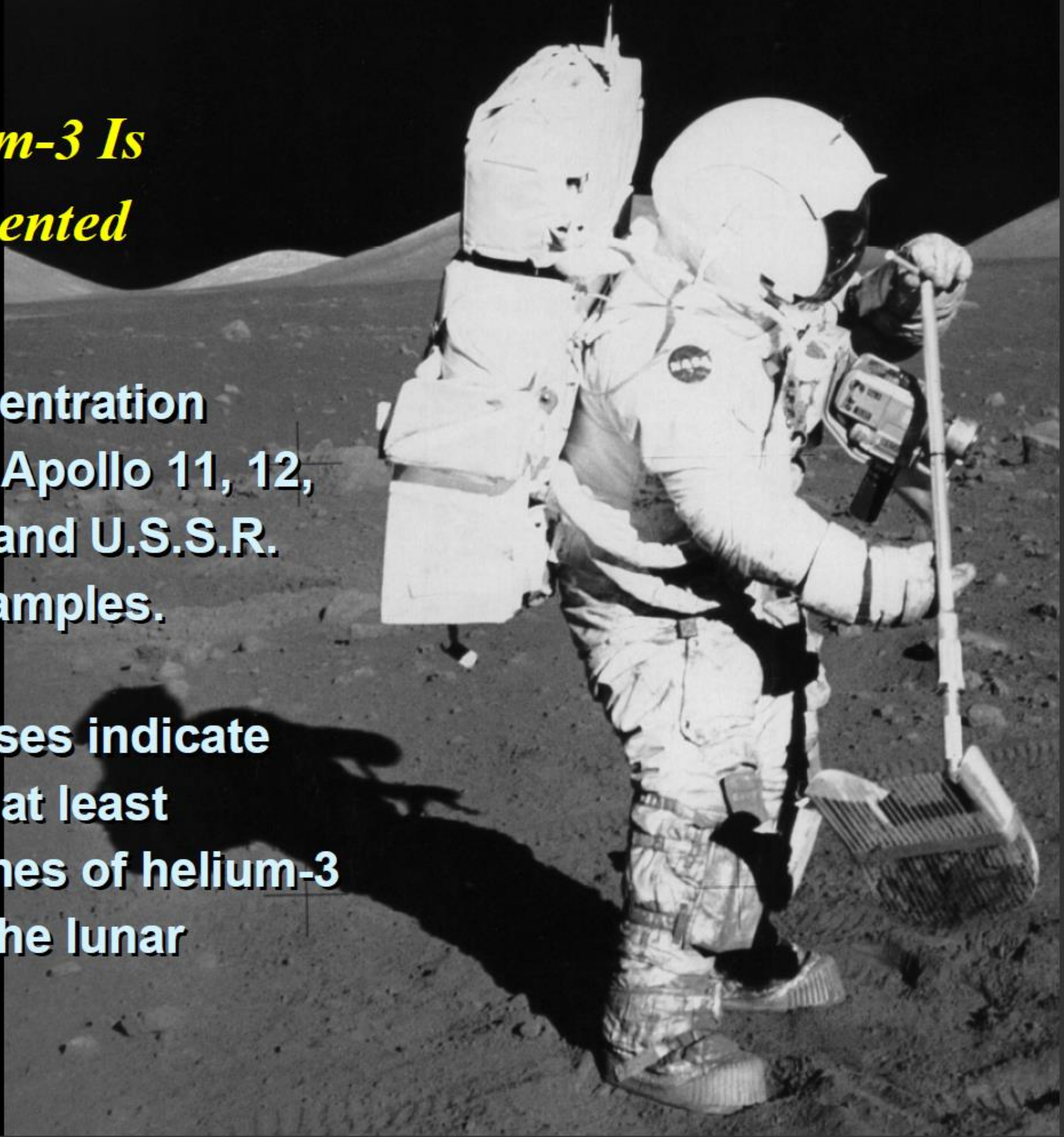
The Number of Neutrons Generated by Helium-3 Fusion Fuels is Very Small



Lunar Helium-3 Is Well Documented

- Helium-3 concentration verified from Apollo 11, 12, 14, 15, 16, 17 and U.S.S.R. Luna 16, 20 samples.

- Current analyses indicate that there are at least 1,000,000 tonnes of helium-3 imbedded in the lunar surface.



G.L. Kulcinski, Fusion Technology Institute, U-Wisconsin, Madison 20th International Space Development Conference, 2001

In 2013 China's Chang'e 3 mission made a successfulsoft landing on the far side, at the south pole.

https://www.youtube.com/watch?v=QzZkF1MAsb8

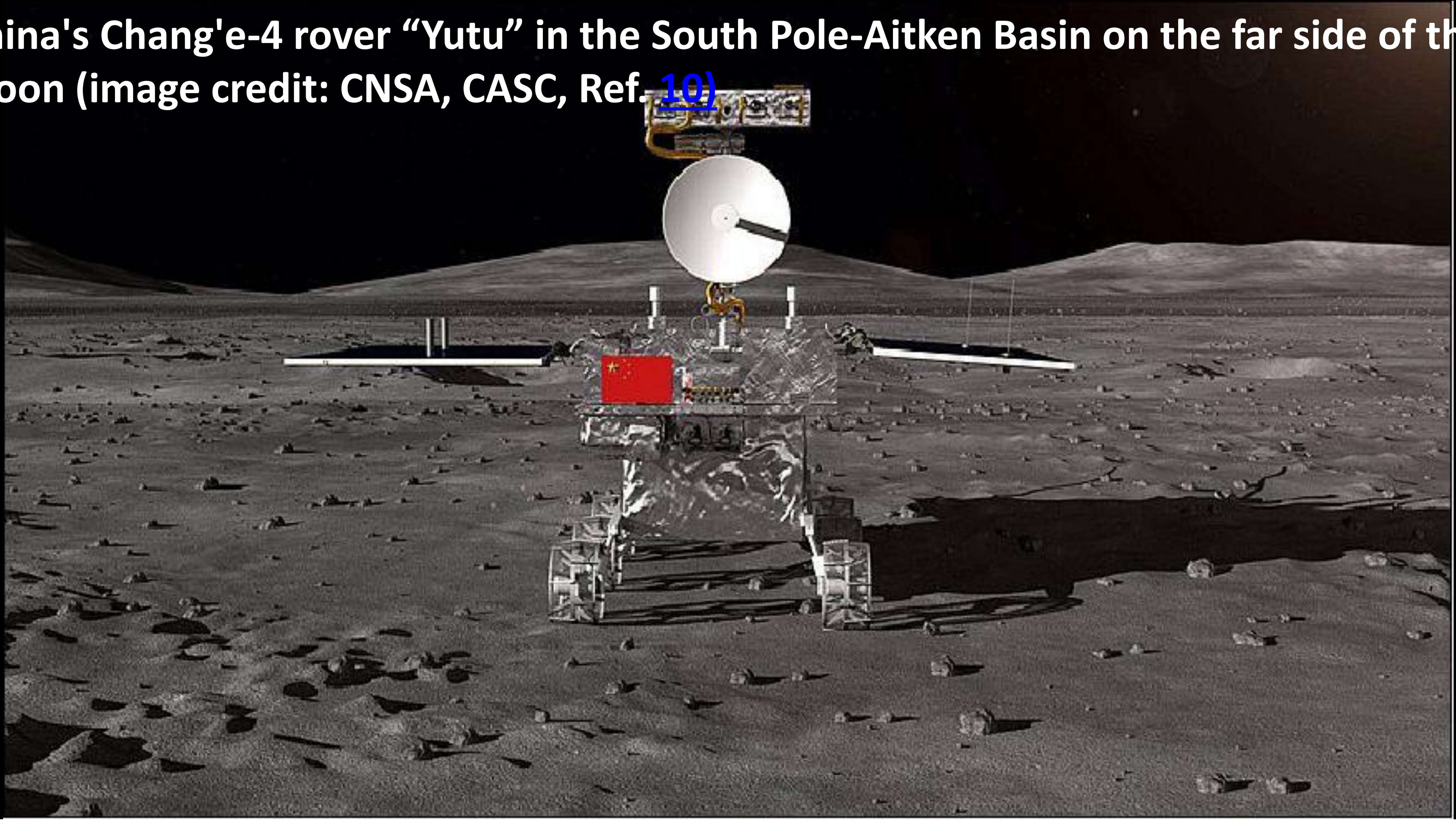
Is there enough He^3 at the lunar south pole to use for safe, renewable nuclear fusion?

China’s Chang’e 4 mission made a soft landing on the far side of the Moon, in the south pole Aitken Basin in January, 2019, looking for He^3 and other elements.

https://www.scmp.com/news/china/science/article/2180587/what-you-need-know-about-change-4-chinas-mission-far-side-moon

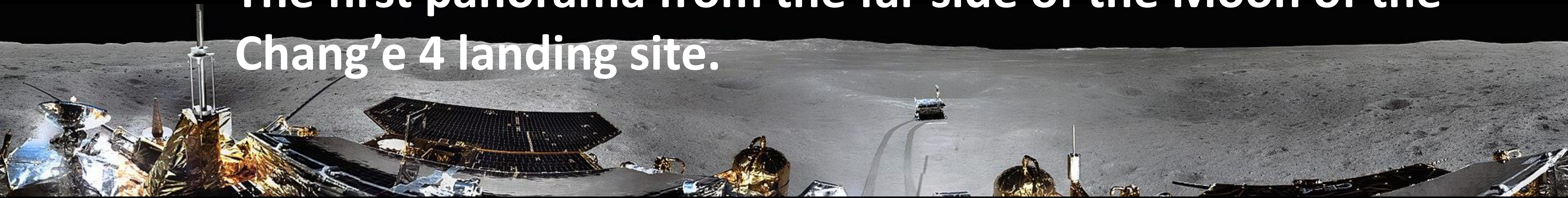
Interesting aside: China's lunar rover discovered a “mysterious” material on far side of Moon which may be impact glass – regolith that was melted from impact – or may be mantle rock.

China's Chang'e-4 rover “Yutu” in the South Pole-Aitken Basin on the far side of the moon (image credit: CNSA, CASC, Ref. 10)



https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/chang-e-4#1w2UR122bHerb

The first panorama from the far side of the Moon of the Chang’e 4 landing site.



See these videos:

https://www.youtube.com/watch?v=gG89jelo5S8

https://www.youtube.com/watch?v=8WqXeGIOiuY

I spent a lot of time looking on line for results from Chang’e 4, which landed on the far side in January, 2019, but there are no results published on the web yet, at least not that I could find.

IS THERE He^3 ON THE FAR SIDE??

RTGs

A radioisotope thermoelectric generator (RTG) is an electrical generator that uses an array of thermocouples to convert the heat released by the decay of a suitable radioactive material into electricity by building up an electric potential across a temperature gradient. This generator has no moving parts.

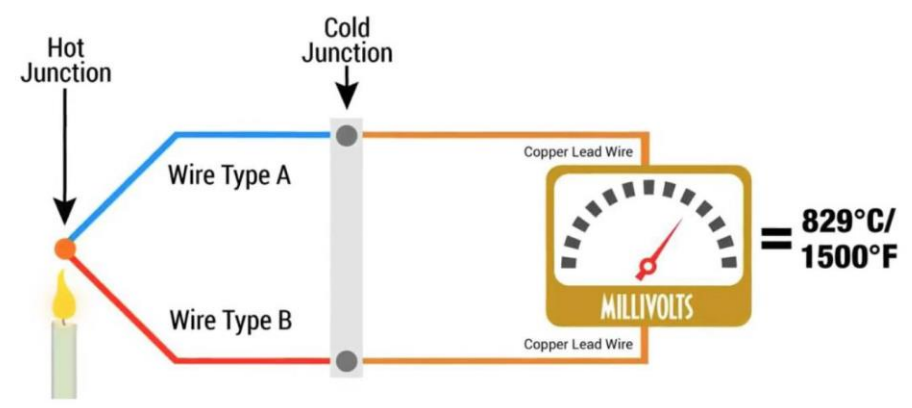
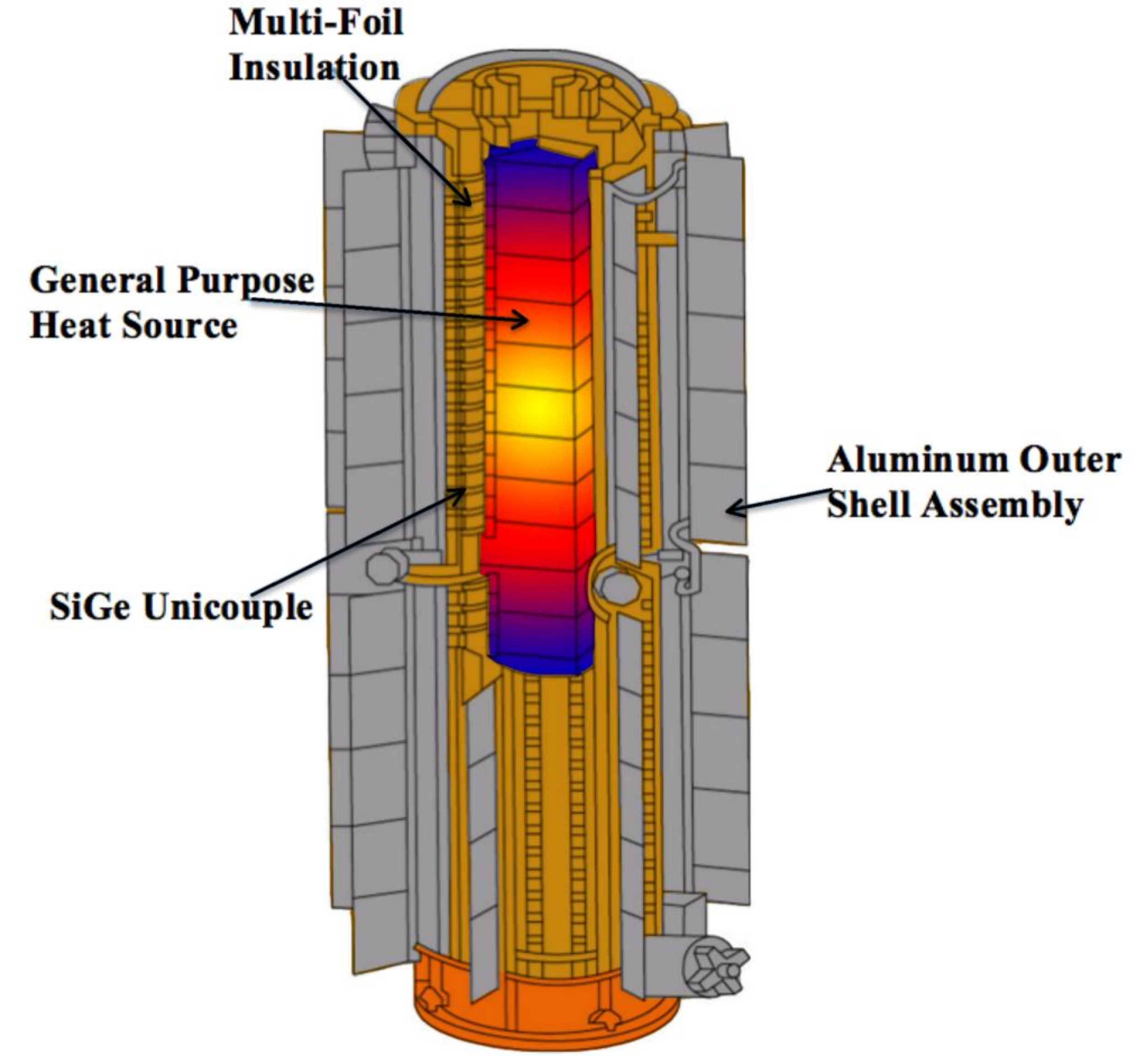


diagram of a thermocouple



Essential components of a SiGe radioisotope thermoelectric generator

Material	Shielding	Power density (W/g)		Half-life (years)	
^{238}Pu	Low	0.54		87.7	
^{90}Sr	High	0.46		28.8	
^{210}Po	Low	140		0.378	
^{241}Am	Medium	0.114		432	

Criteria for selection of isotopes:

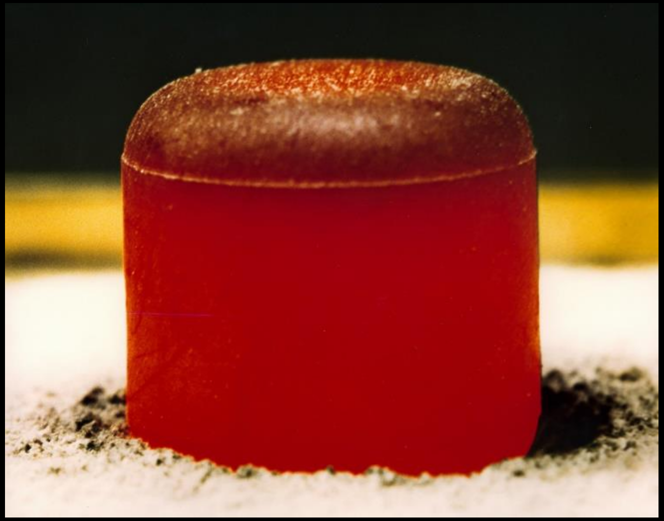
1. Must have sufficiently long ½ life

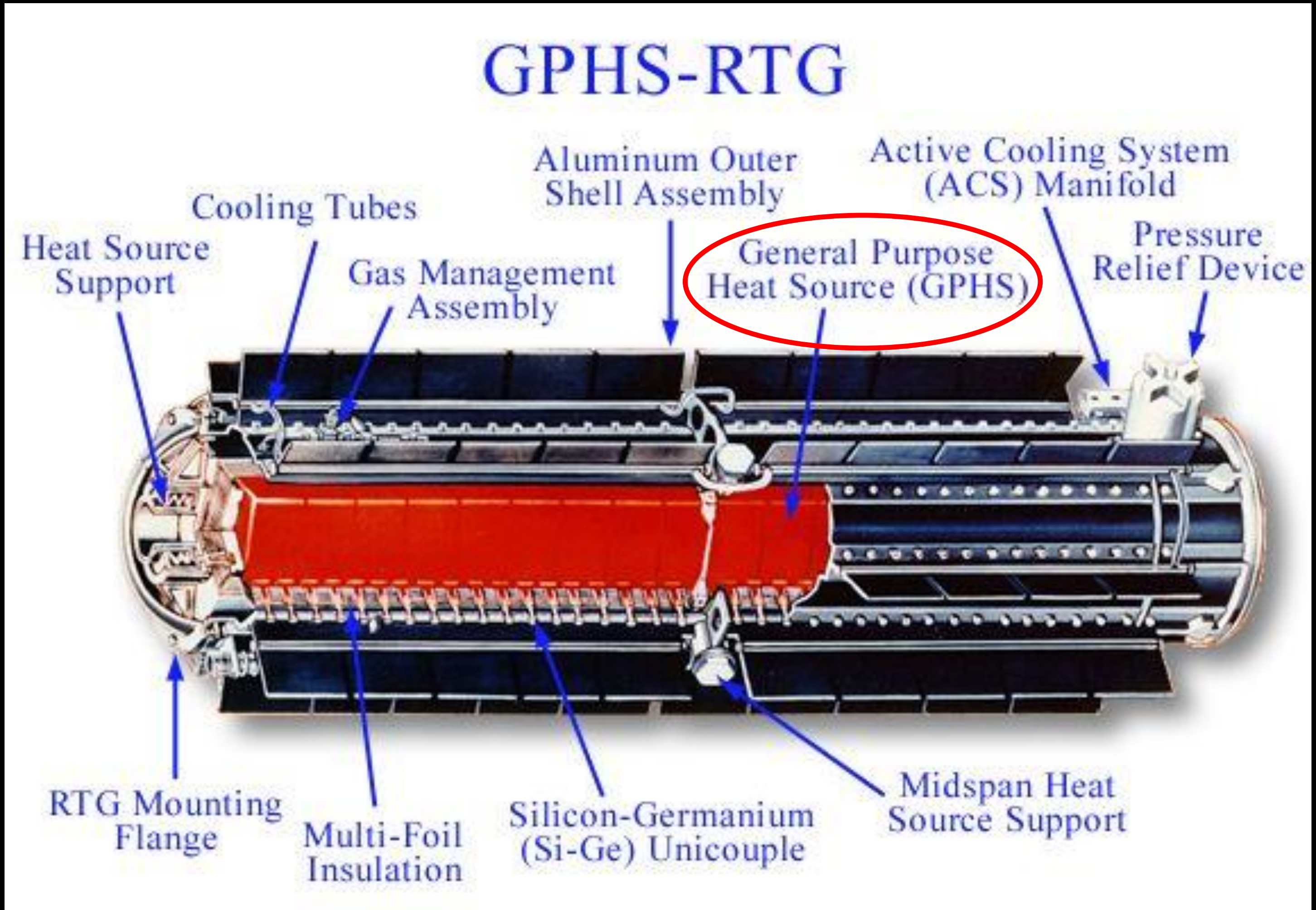
2. Must produce a large amount of power per mass and volume.

Alpha emitters release ~ 10x as much energy as beta.

3. Radiation must be easily absorbed and converted to heat

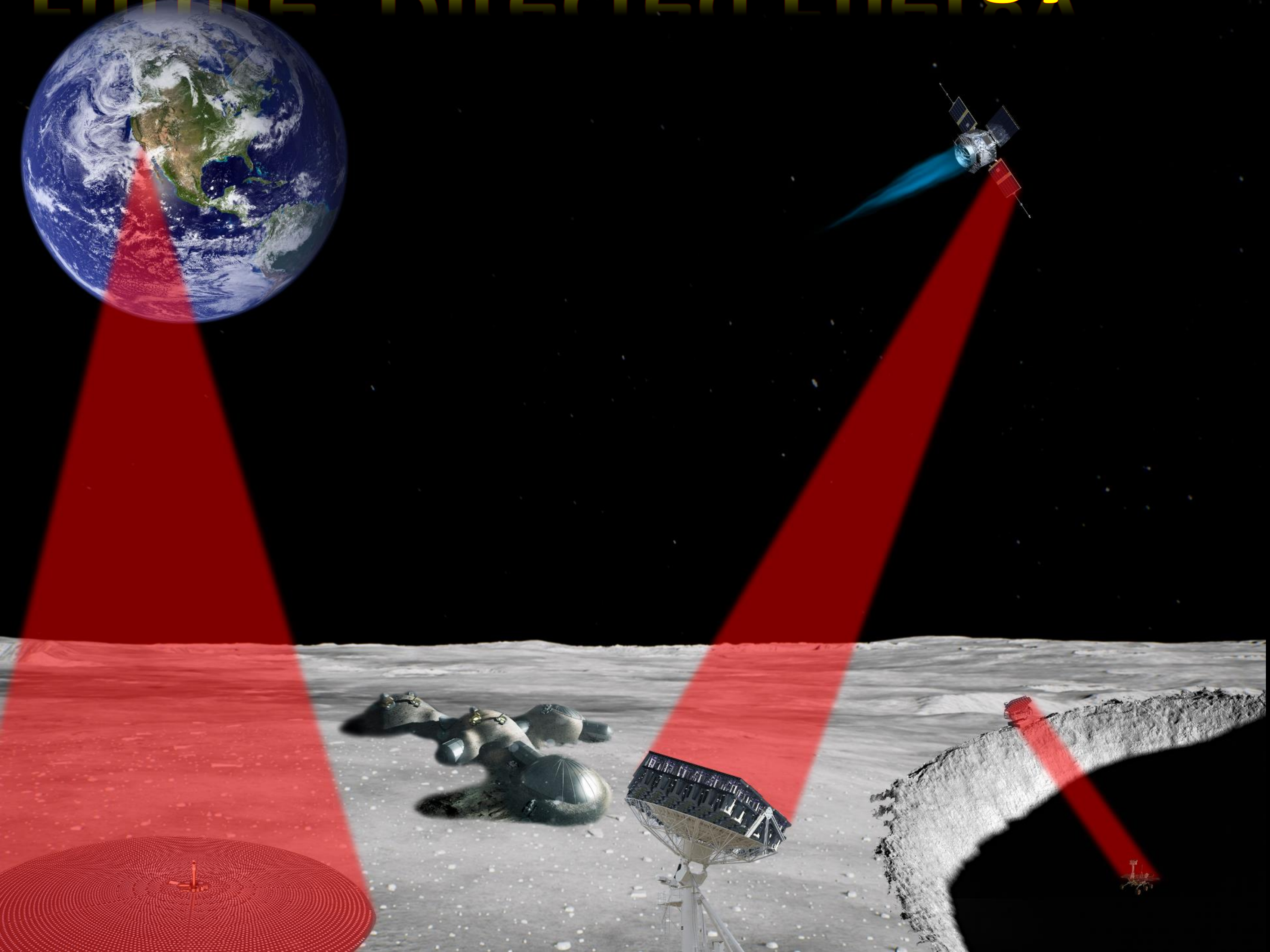
https://en.wikipedia.org/wiki/Radioisotope_thermoelectric_generator





A pellet of $^{238}PuO_2$ as used in the RTG for the *Cassini* and *Galileo* missions. This photo was taken after insulating the pellet under a graphite blanket for several minutes and then removing the blanket. The pellet is glowing red hot because of the heat generated by radioactive decay (primarily α). The initial output is 62 watts.

Future: Directed Energy

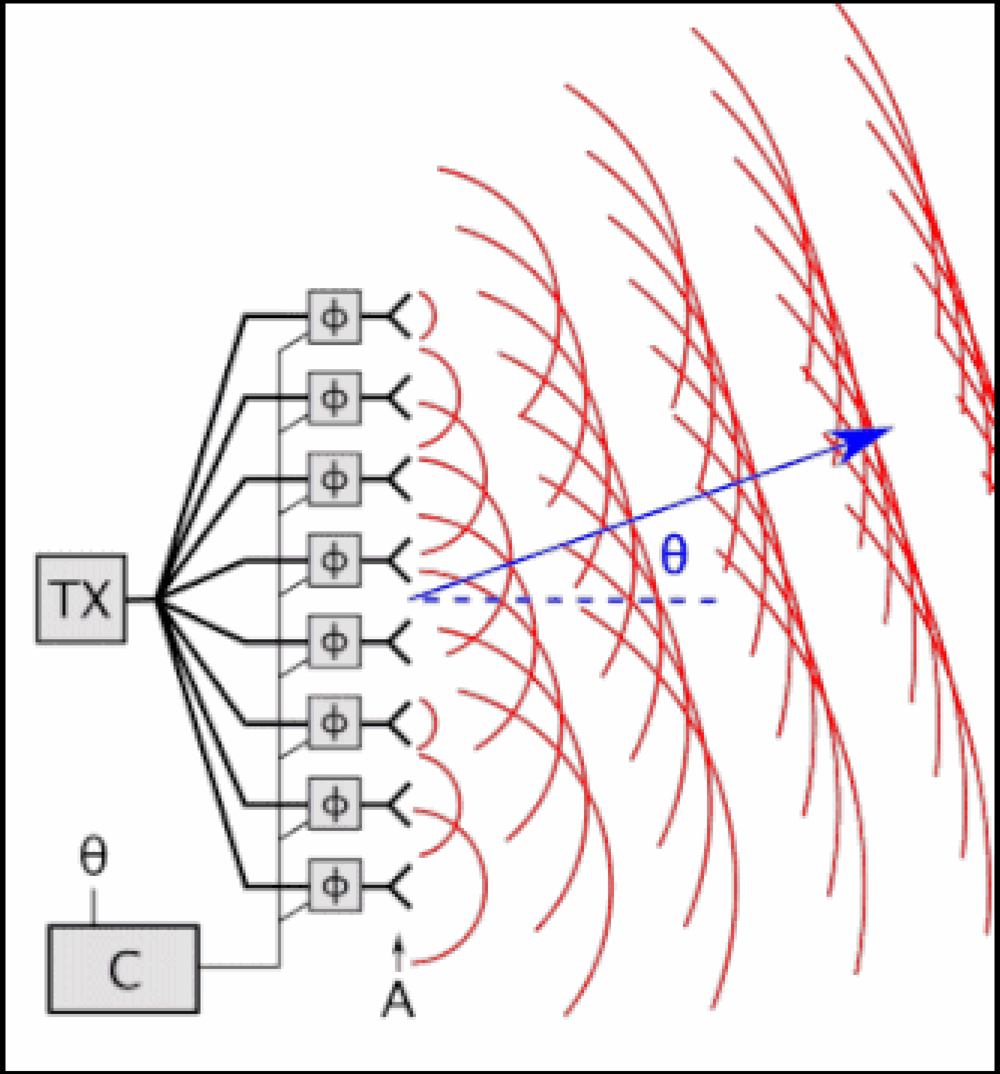


Proposed directed energy power from Earth (ground or orbit) to the Moon from a laser phased array (left).

An array on the Moon is shown beaming power to a spacecraft bound for Mars (right).

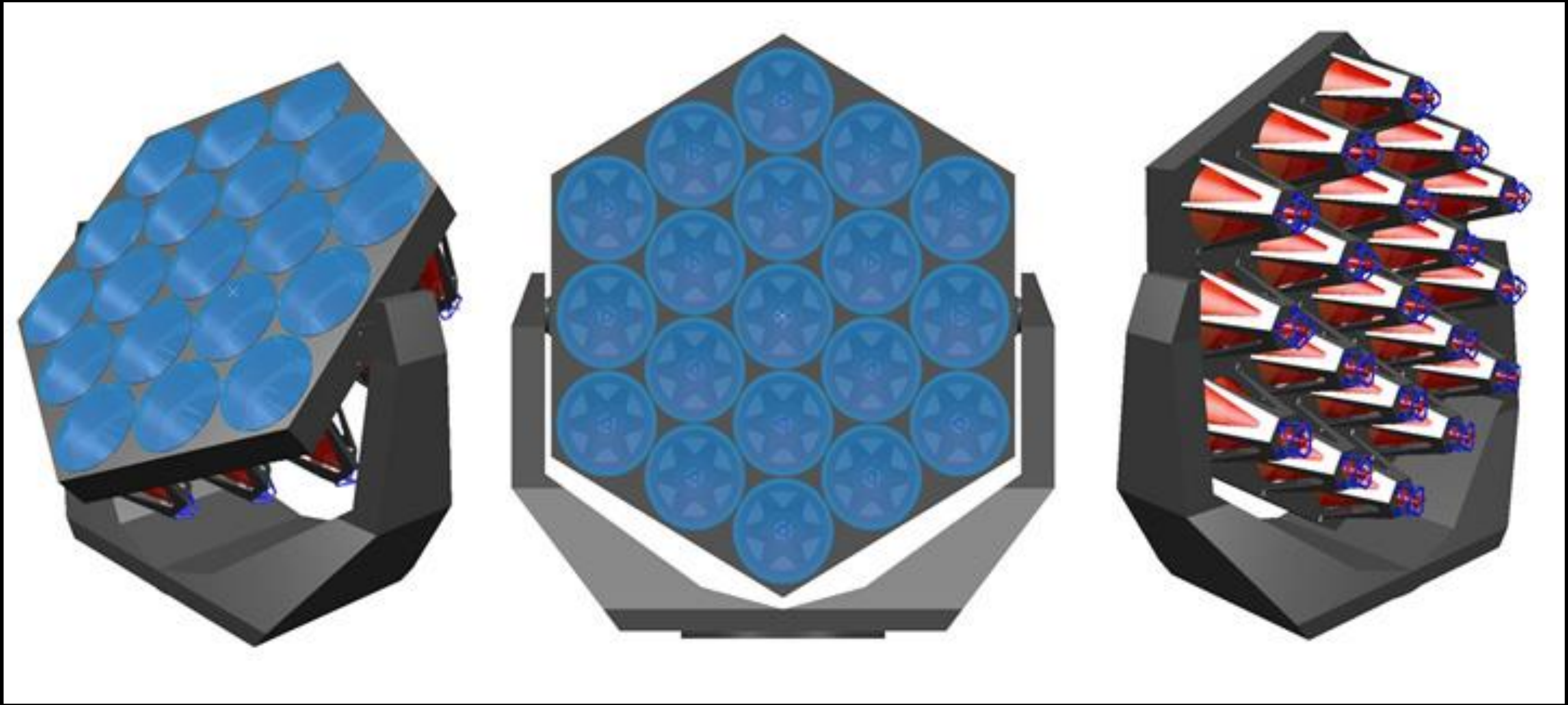
A smaller array is shown beaming power into a PSR (far right).

Lubin, 2020 proprietary image



Animation showing how a phased array works. It consists of an array of antenna elements *(A)* powered by a transmitter *(TX)*. The feed current for each antenna passes through a phase shifter *(φ)* controlled by a computer *(C)*. The moving red lines show the wavefronts emitted by each element. The individual wavefronts are spherical, but they combine (superpose) in front of the antenna to create a plane wave travelling in a specific direction. The phase shifters delay the waves progressively going up the line so each antenna emits its wavefront later than the one below it. This causes the resulting plane wave to be directed at an angle ϑ to the antenna's axis. By changing the phase shifts the computer can instantly change the angle ϑ of the beam. Most phased arrays have two-dimensional arrays of antennas.

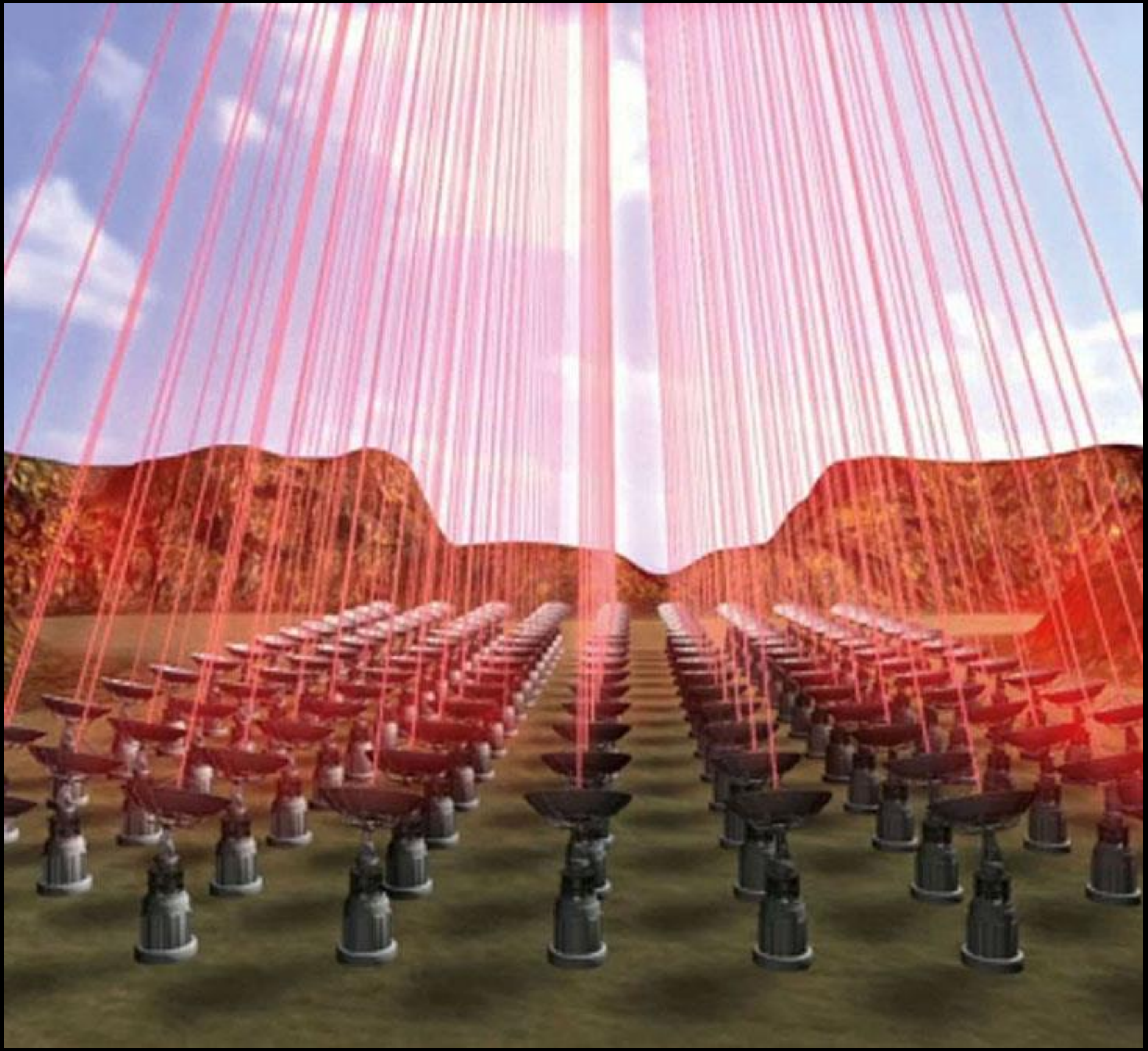
a U.S. Army Research Laboratory 19-channel Coherent Fiber Laser Array System. ***(Photo Credit: U.S. Army photo)***



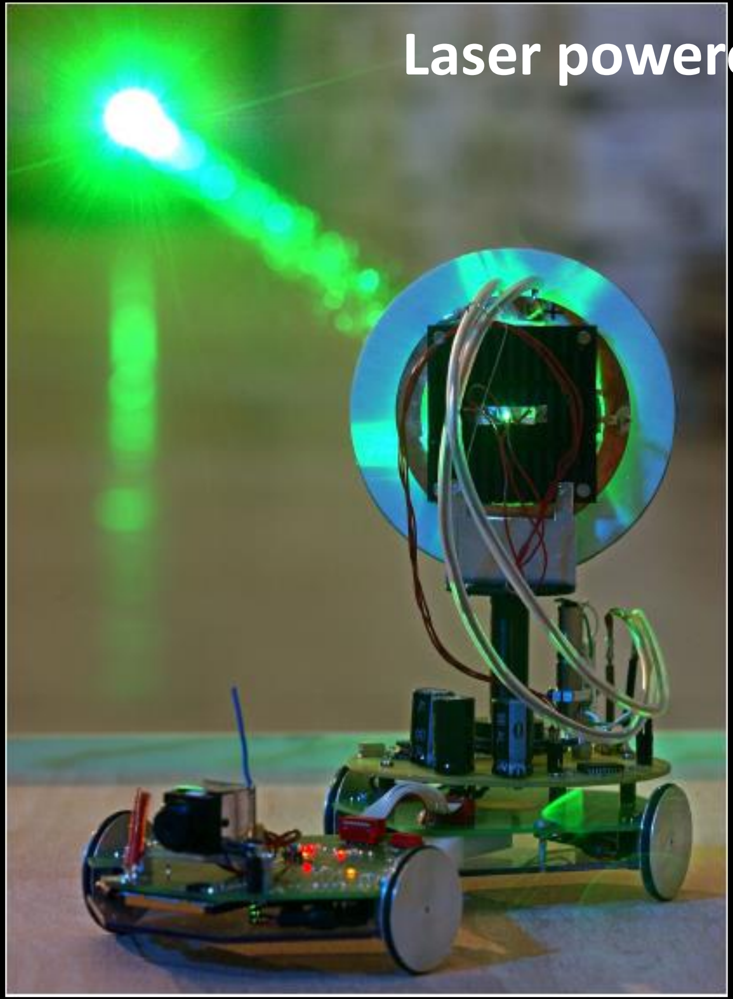
Drawing of a 19-element laser phased array. Array can be tilted, and each element can be pointed and focused, and each fiber is tuned to be in phase. – Lubin, et al.

The system can be used to beam power to very distant spacecraft or to provide power to distant outposts on Mars or the Moon or literally to machines on the lunar surface (or possibly Mars).
– Lubin, et al. ~2017

https://www.youtube.com/watch?time_continue=5&v=WCDuAiA6kX0&feature=emb_logo



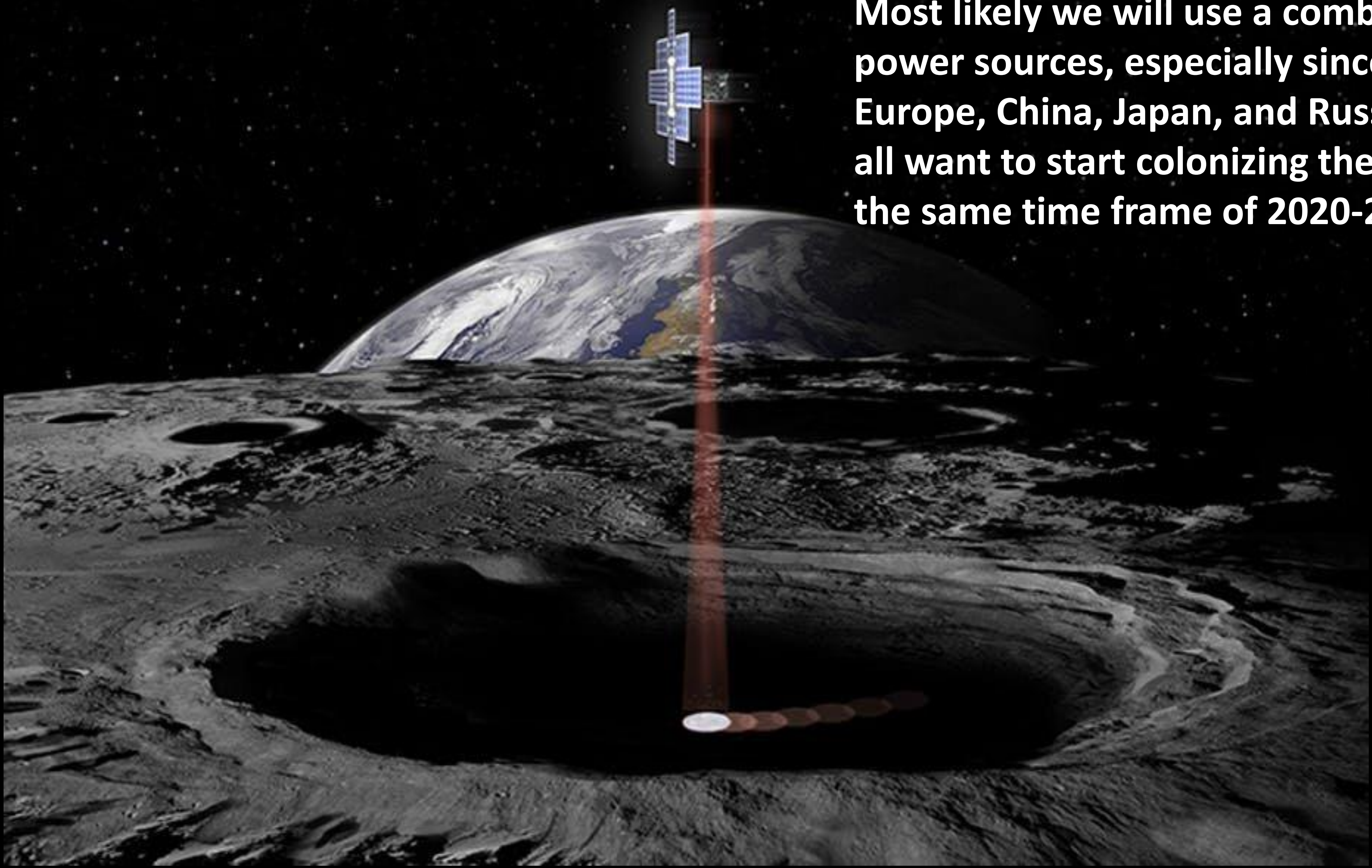
Laser powered rover - ESA



Solar powered satellite beaming directed energy to power a lunar base –
concept by JAXA

Concepts for wireless energy transmission via laser

Leopold Summerer, Oisin Purcell
ESA - Advanced Concepts Team
Keplerlaan 1, NL-2201AZ Noordwijk, The Netherlands,
Leopold.Summerer@esa.int, +31-71-565-6227



Most likely we will use a combination of power sources, especially since the US, Europe, China, Japan, and Russia appear to all want to start colonizing the Moon in the same time frame of 2020-2024.