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Frontiers of Space Power and Energy

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Introduction

Space faring, including space exploration, commercialization, and colonization, requires serious levels of power and energy. It is required for in-space and on-body propulsion, habitats and transportation, In Situ Resource Utilization (ISRU), manufacturing, life support, robotics, satellites, sensors, and construction. The current power and energy sources being applied and under development include solar energy, chemical fuels, radioisotope thermoelectric generator (RTG) nuclear batteries, and fission nuclear reactors. There are problems with each of these including reductions in solar intensity farther from the Sun and due to dust, ISRU resource processing requirements, storage, transfer of chemical fuels and the weight, energy density, and safety of the current nuclear approaches [ref. 1]. Alternative energy sources could reduce cost and weight and improve safety, efficiency, and functionality. Particularly interesting alternatives include the recent invention of very high energy density, low weight nuclear batteries that have orders of magnitude greater energy density than RTGs and orders of magnitude less weight than reactors with scalability from milliwatts to tens of megawatts. This approach appears to be capable of powering everything space-related, from small sensors to Vasimir, which would provide fast, 200-day Mars round trips with 6,000 seconds of Isp. Additionally, this battery could power tethers working off the Earth's magnetic field to, fuellessly, collect space debris and repurpose such via in-space remanufacturing. Additional frontier power and energy approaches include regeneration, utilization of heat losses via various energy conversion methods to improve efficiency, reduce weight, and cost of energy generation and heat rejection systems. Also, there are much more efficient and smaller multi-phase space radiator approaches. There are a myriad of energy storage approaches and beyond chemical there are exotics, including positrons, which have orders of magnitude greater energy density than fission with no residual radiation and affordable.This report will first discuss current NASA energetics technologies and then the various frontier space power and energy alternatives mentioned briefly above.

Summary of NASA Approaches to Power and Energy for the Moon and Mars

Long stays on the Moon suggests a level of infrastructure more substantial than the Apollo era assets delivered during the last time astronauts set foot on the Moon. Those previous missions were short stays lasting a matter of hours and required nothing more than the items onboard the mission modules to safely return the crew back to Earth. Longer term stays [Figure 1] will require that items be brought by other missions before, during, and after each crew arrives [ref. 2].

Even so, some items such as radiation shielding for Galactic Cosmic Rays (GCR) and blast berms may be too massive to bring from Earth. ISRU on the Moon may offer inexpensive substitutes for bringing much needed crew protection from Earth. Three to five meters depth of lunar regolith can shield astronauts from GCR radiation and micrometeorite impacts and provide thermal insulation [ref. 3]. Also, bound chemically with other elements in the lunar regolith are oxides, as much as 40% by mass. They can be processed (with some difficulty) into breathable oxygen and oxidizers for fuel. There are also indications of water on the Moon in some locations.

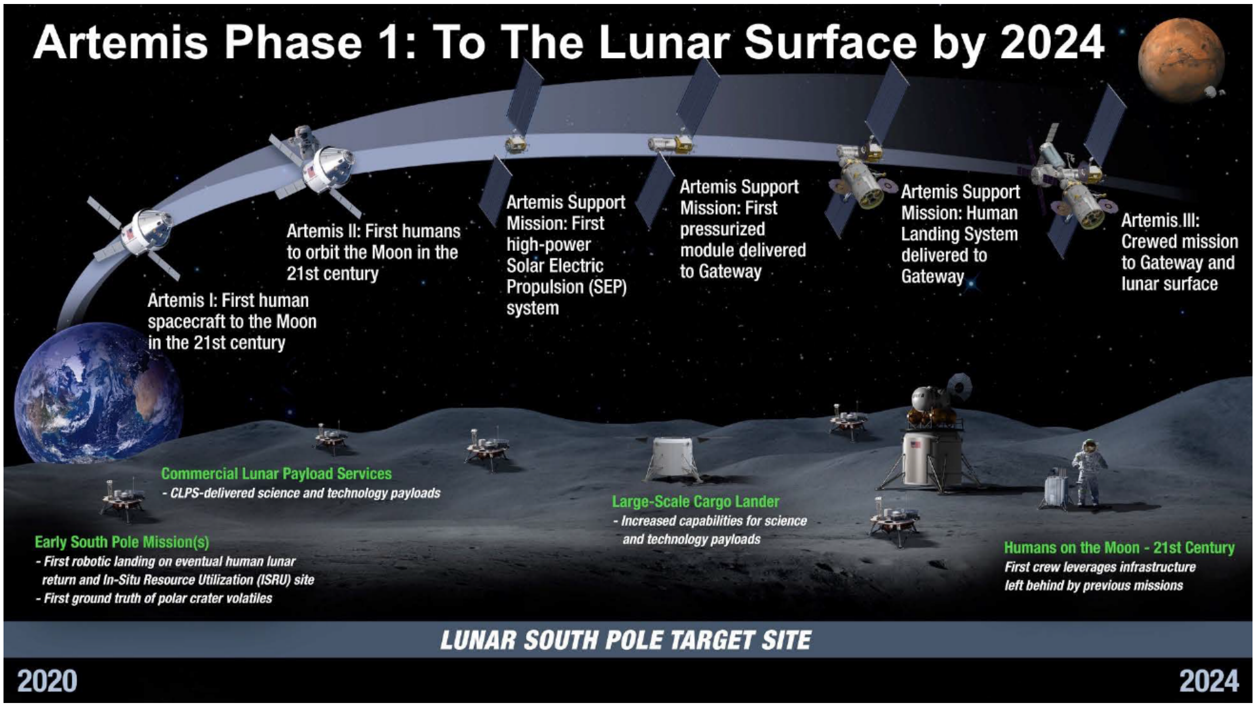


Figure 1: Artemis Phase 1 Showing Buildup of Surface Assets Beginning in 2020 to Support an Astronaut Mission in 2024 [Courtesy of NASA, https://www.nasa.gov/specials/artemis/]

Moving large amounts of regolith seems doable using construction equipment concepts in development at NASA Kennedy Space Center [ref. 4]. Since this work can be spread over many days, existing power technologies in solar cells and radioisotope thermoelectric generators (RTGs) may be sufficient. However, processes aimed at heating regolith at high temperatures to release oxides or to liquefy or sinter regolith for additive manufacturing and construction, require much higher power levels than solar cells and RTGs may be able to supply.

Preliminary assessments of power requirements for the Lunar Pole (near continuous light), shown in Figure 2, and non-Polar (340 hours sunlight, 340 hours darkness), shown in Figure 3, suggest power levels well above 10kW, with 20kW required for ISRU and 20Kw required for rovers. NASA has established an overall innovation goal of achieving 100 W/kg power density and has supported a variety of development projects to achieve power systems capable of meeting that goal:

Space Technology Mission Directorate (STMD) – Game Changing Investments

- Nuclear Systems – Krusty/Kilopower (2012 – present)
- Regenerative Fuel Cell Project (2018 – present)
- Extreme Environment Solar Power Project (2015 – present)
- Lunar Lander Fuel Cells ACO & Tipping Point [Blue Origin] (2020 – TBD)
- Flexible Solar Arrays qual Protocols ACO [Maxar] (2020 – TBD)
- Adaptable Lunar Lander Solar Array Systems Study (2019 – 2020)
- Solar Arrays With Storage Seedling Study (2017)
- Advanced Space Power Systems (2012-2015)
- Solar Electric Propulsion Solar Array Systems [MegaFlex, ROSA] (2012-2015)

Science Mission Directorate (SMD) Investments

- NextGen RTGs
- Dynamic RPS

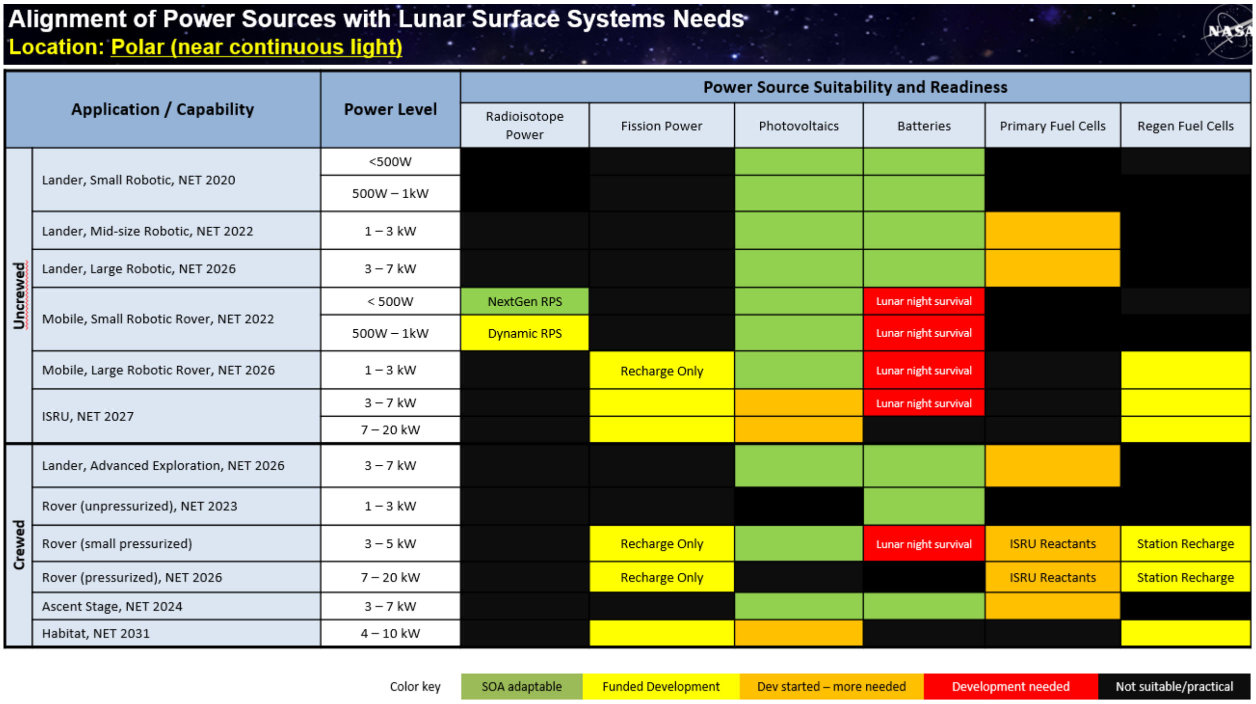
Human Exploration and Operations Mission Directorate (HEOMD) Investments

- Advanced Modular Power Systems
- Autonomous Power Control
- Non-Flow-Thru Fuel Cell Advancement

Since 2012, in anticipation of future moon and mars exploration activities such as shown on Figures 4 and 5, NASA has been developing the nuclear fission concept called KRUSTY (Kilopower Reactor Using Stirling Technology) [ref. 5]. Potential applications include nuclear electric propulsion and a steady electricity supply for crewed or robotic space missions that require large amounts of power, especially where sunlight is limited or not available. NASA has also studied the Kilopower/KRUSTY reactor as the power supply for crewed Mars missions. During those missions, the reactor would be responsible for powering the machinery necessary to separate and cryogenically store oxygen from the Martian atmosphere for ascent vehicle propellants. Once humans arrive, the reactor would power their life-support systems and other requirements. NASA studies have shown that a 40 kWe reactor would be sufficient to support a crew of four to six astronauts. The space-rated 10 kWe Kilopower for Mars is expected to mass 1500 kg in total (with a 226 kg core) and contain 43.7 kg of U-235 [ref. 6]. That results in a power density around 6 W/kg, far below the goal of 100 W/kg.

These preliminary requirements for power suggest that several KRUSTY devices would be required to meet power demands. Currently standing several meters tall, KRUSTY does not look portable. Also, its selection of fission material requires that it be placed far away from crew, thus requiring an elaborate power management and distribution system to transmit power to points of use. Fission power will require radiation stand-off distances over 1km, which presents technology challenges in lightweight, high voltage cables, robotic deployment, and high voltage power conditioning. This standoff distance could be shortened if blast berms and other precautions to protect the crew in the event of an accident could be implemented using construction techniques and equipment suitable for lunar operations. Despite serious limitations on power applications due to its mass and size, Kilopower may pave the way for launch and use of fission power in crew missions beyond Low Earth Orbit [ref. 7].

To meet the demands for portable power, other options are being explored. These include radioisotopes, photovoltaics, batteries, and fuel cells. Rover recharging stations at the bottom of solar power towers are being considered for meeting mobility demands [ref. 8]. But, these do not provide the high-power densities necessary to heat regolith to high temperatures or to power equipment performing additive manufacturing, construction, and mining tasks. One concept uses the Cassegrain system to focus sunlight onto regolith to print landing pads and to stabilize berms [ref. 9]. However, this Cassegrain system may not be sufficiently mobile for other applications requiring portable high-power densities. Continuous power beaming from stationary generators to points of use, both static and mobile, is also a consideration.

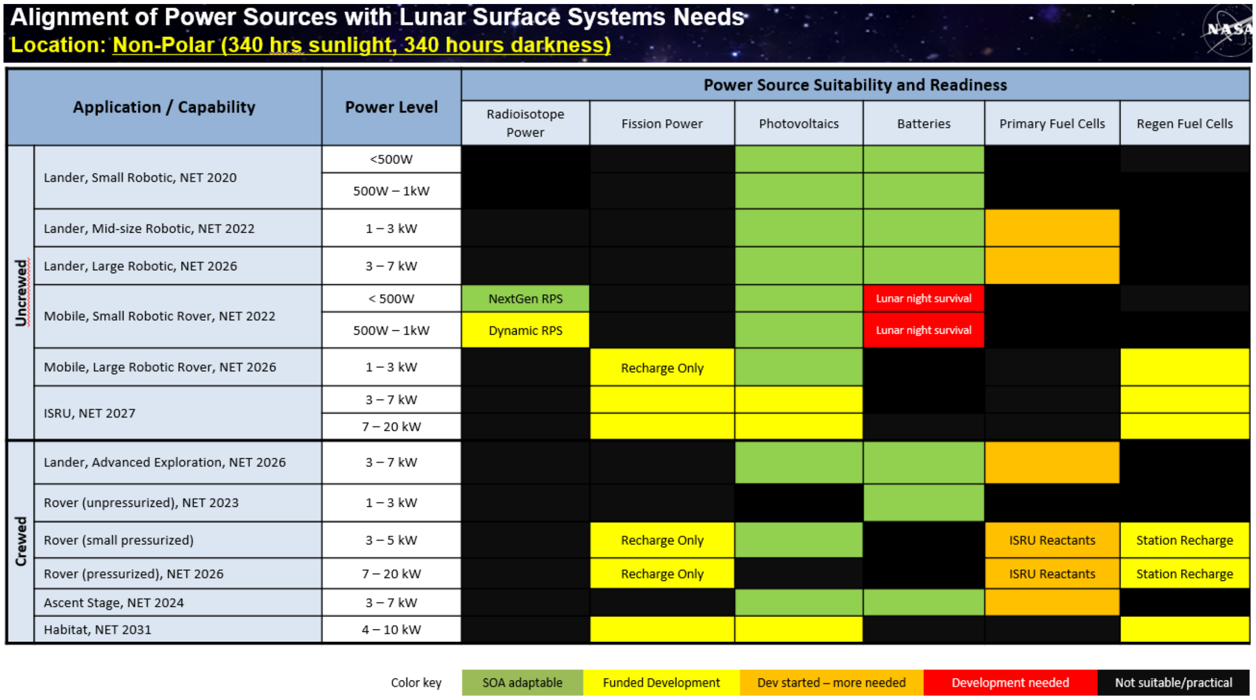


Alignment of Power Sources with Lunar Surface Systems Needs
Location: Polar (near continuous light)

	Application / Capability	Power Level	Power Source Suitability and Readiness					
			Radioisotope Power	Fission Power	Photovoltaics	Batteries	Primary Fuel Cells	Regen Fuel Cells
Uncrewed	Lander, Small Robotic, NET 2020	<500W	⬛	⬛	🟩	🟩	⬛	⬛
		500W – 1kW	⬛	⬛	🟩	🟩	⬛	⬛
	Lander, Mid-size Robotic, NET 2022	1 – 3 kW	⬛	⬛	🟩	🟩	🟧	⬛
	Lander, Large Robotic, NET 2026	3 – 7 kW	⬛	⬛	🟩	🟩	🟧	⬛
	Mobile, Small Robotic Rover, NET 2022	< 500W	🟩 NextGen RPS	⬛	🟩	🟥 Lunar night survival	⬛	⬛
		500W – 1kW	🟨 Dynamic RPS	⬛	🟩	🟥 Lunar night survival	⬛	⬛
	Mobile, Large Robotic Rover, NET 2026	1 – 3 kW	⬛	🟨 Recharge Only	🟩	🟥 Lunar night survival	⬛	🟨
	ISRU, NET 2027	3 – 7 kW	⬛	🟨	🟧	🟥 Lunar night survival	⬛	🟨
		7 – 20 kW	⬛	🟨	🟧	⬛	⬛	🟨
Crewed	Lander, Advanced Exploration, NET 2026	3 – 7 kW	⬛	⬛	🟩	🟩	🟧	⬛
	Rover (unpressurized), NET 2023	1 – 3 kW	⬛	⬛	⬛	🟩	⬛	⬛
	Rover (small pressurized)	3 – 5 kW	⬛	🟨 Recharge Only	🟩	🟥 Lunar night survival	🟧 ISRU Reactants	🟨 Station Recharge
	Rover (pressurized), NET 2026	7 – 20 kW	⬛	🟨 Recharge Only	⬛	⬛	🟧 ISRU Reactants	🟨 Station Recharge
	Ascent Stage, NET 2024	3 – 7 kW	⬛	⬛	🟩	🟩	🟧	⬛
	Habitat, NET 2031	4 – 10 kW	⬛	🟨	🟧	⬛	⬛	🟨

Color key: 🟩 SOA adaptable 🟨 Funded Development 🟧 Dev started – more needed 🟥 Development needed ⬛ Not suitable/practical

Figure 2: Alignment of Power Sources with Lunar Surface System's Needs, Based on Current Knowledge of Available Power Technologies, at the Moon's South Polar Regions Near Continuous Sunlight [Credit: APL Power Technology Review Meeting, NASA GRC, November 4, 2019]



Alignment of Power Sources with Lunar Surface Systems Needs
Location: Non-Polar (340 hrs sunlight, 340 hours darkness)

	Application / Capability	Power Level	Power Source Suitability and Readiness					
			Radioisotope Power	Fission Power	Photovoltaics	Batteries	Primary Fuel Cells	Regen Fuel Cells
Uncrewed	Lander, Small Robotic, NET 2020	<500W	⬛	⬛	🟩	🟩	⬛	⬛
		500W – 1kW	⬛	⬛	🟩	🟩	⬛	⬛
	Lander, Mid-size Robotic, NET 2022	1 – 3 kW	⬛	⬛	🟩	🟩	🟧	⬛
	Lander, Large Robotic, NET 2026	3 – 7 kW	⬛	⬛	🟩	🟩	🟧	⬛
	Mobile, Small Robotic Rover, NET 2022	< 500W	🟩 NextGen RPS	⬛	🟩	🟥 Lunar night survival	⬛	⬛
		500W – 1kW	🟨 Dynamic RPS	⬛	🟩	🟥 Lunar night survival	⬛	⬛
	Mobile, Large Robotic Rover, NET 2026	1 – 3 kW	⬛	🟨 Recharge Only	🟩	⬛	⬛	🟨
	ISRU, NET 2027	3 – 7 kW	⬛	🟨	🟨	⬛	⬛	🟨
		7 – 20 kW	⬛	🟨	🟨	⬛	⬛	🟨
Crewed	Lander, Advanced Exploration, NET 2026	3 – 7 kW	⬛	⬛	🟩	🟩	🟧	⬛
	Rover (unpressurized), NET 2023	1 – 3 kW	⬛	⬛	⬛	🟩	⬛	⬛
	Rover (small pressurized)	3 – 5 kW	⬛	🟨 Recharge Only	🟩	⬛	🟧 ISRU Reactants	🟨 Station Recharge
	Rover (pressurized), NET 2026	7 – 20 kW	⬛	🟨 Recharge Only	⬛	⬛	🟧 ISRU Reactants	🟨 Station Recharge
	Ascent Stage, NET 2024	3 – 7 kW	⬛	⬛	🟩	🟩	🟧	⬛
	Habitat, NET 2031	4 – 10 kW	⬛	🟨	🟨	⬛	⬛	🟨

Color key: 🟩 SOA adaptable 🟨 Funded Development 🟧 Dev started – more needed 🟥 Development needed ⬛ Not suitable/practical

Figure 3: Alignment of Power Sources with Lunar Surface System's Needs, Based on Current Knowledge of Available Power Technologies, at the Moon's Non-Polar Regions with Alternating Periods of Sunlight (340 Hours Sunlight, 340 Hours Darkness) [Credit: APL Power Technology Review Meeting, NASA GRC, November 4, 2019]

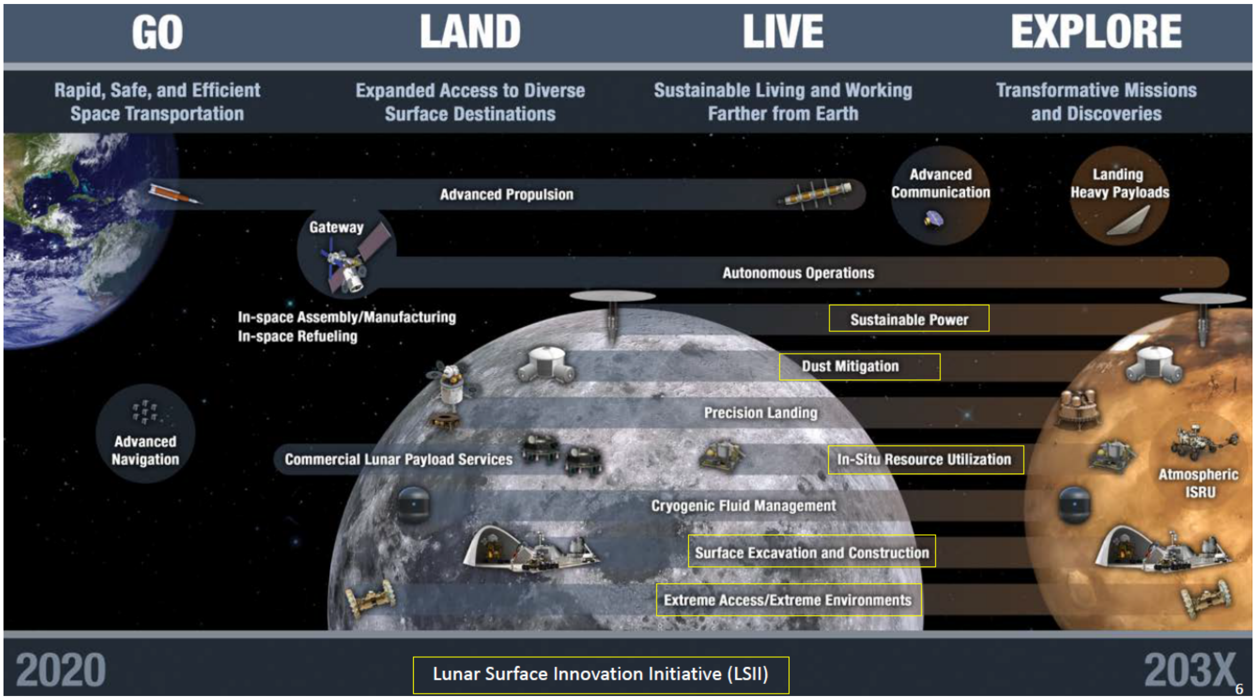


Figure 4: Artemis Phase 2 Prepares for Mars [Courtesy of NASA, https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf]

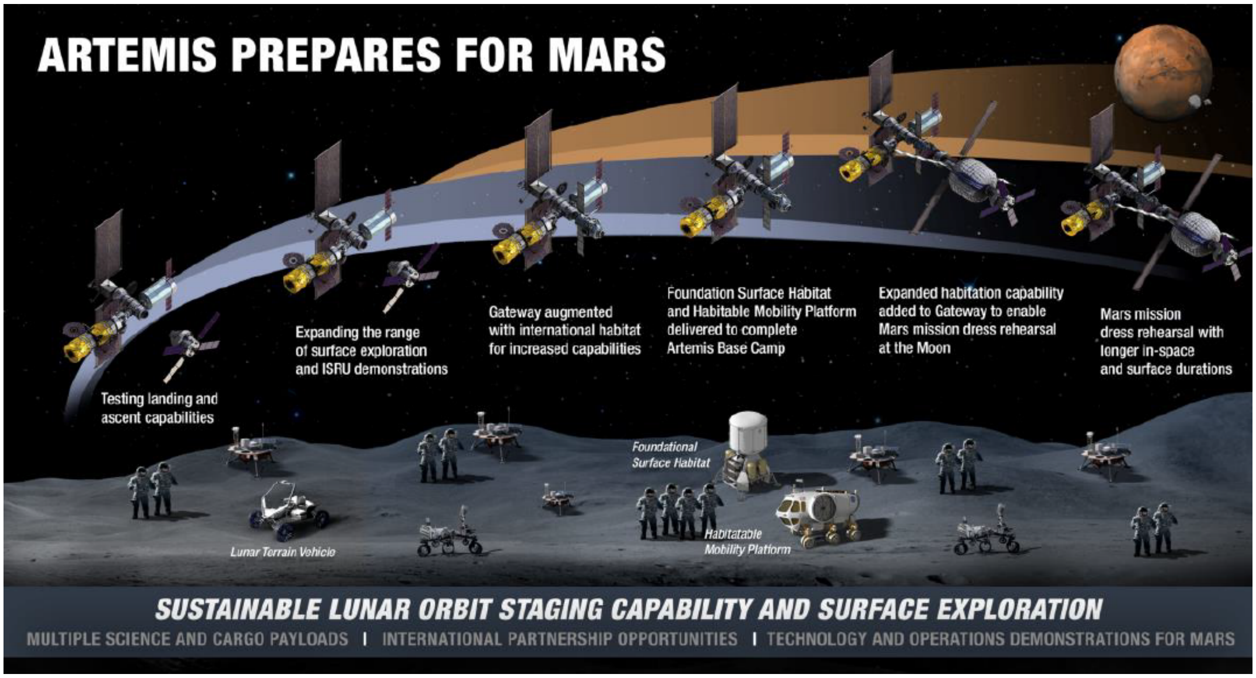


Figure 5: Lunar Surface Innovation Initiative (LSII) Timeline and Six Technology Areas for Enabling NASA's Moon to Mars Program [Courtesy of NASA]

There may be other near-term and long-term technologies that could meet the power demands on the Moon to support long stays. However, it is unclear how these power system architectures, especially those using sunlight, will translate to sustainable power for humans-Mars missions. On Mars, the intensity of sunlight is less than half the intensity on the Moon. At first glance, few (if any) of the power concepts being considered for the Moon look capable of fulfilling the expected needs of crews staying for long durations on Mars that could lead to a sustainable presence. As illustrated, sustainability demands extensive in situ resource utilization and a reusable lander fueled by converting Martian water to propellant, while also making plastics and many other items on Mars to reduce reliance on Earth [ref. 10]. Many of the systems to conduct these functional capabilities, most which are at remote locations away from the main habitat by mobile assets within a human exploration zone (HEZ), require portable power at higher demands than KRUSTY is capable of delivering [ref. 11].

The current sketches for Artemis Phase 2 [Figures 4 and 5] show very little in the way of surface power concepts. The sketches are intended for building capabilities for Mars Missions beginning around year 2025. The Lunar Surface Innovation Initiative (LSII) illustrates that KRUSTY is the only option being explored to support surface activities during Mars Missions. Solely depending on KRUSTY seems insufficient to meet demands, based on our understanding of sustainable Mars Mission architectures.

Survey of Frontier Power and Energy Technologies and Approaches

Fission Reactors - Thus far the only countries launching nuclear reactors into space has been the province of Russia and the U.S. Russia launched 31 BES-5 fission reactors into space to power RORSATs starting in the 1960s using thermal electric energy conversion. Also starting in the 60s, Russia launched the TOPAZ small fission reactor (10 Kwe) using thermionic conversion. The U.S. launched the SNAP 10 [A] in the 60s and in the 80s started development of the SNAP 100. Unfortunately that project was canceled before flight. More recently in the U.S., several micro nucs have been studied including Rapid-L and AMTEC, with the most recent one, Kilopower, on a development path for utilization on the Moon [ref. 12].

There are several notable benefits of fission reactors, the most important of which is years of high-power output. Before the invention of nuclear batteries with a weight the order of 100 times less than fission reactors and easily scalable up and down and far less expensive, fission reactors were the only cogent source of high power levels over years. The down sides of fission reactors are many, including launch safety, safety in use (especially with regard to human missions), major size and weight driven by radiation protection, and protection from crushing, fires, impact, and explosions. There are ongoing efforts that offer somewhat reduced size, weight, and improved safety. Worldwide there is a plethora of small/miniature reactors under development. There are also traveling wave reactors and a Russian vortex pebble bed design with greatly improved power density. Going forward, human missions will require 24/7/365 availability of high-power levels for habs and ISRU. As a result, fission reactors, probably supplanted or supplemented by nuclear batteries, will be a mainstay of Moon and Mars human exploration, exploitation, and colonization [ref. 13]. All nuclear, and other power generation development will need to optimize advanced radiator and energy regeneration approaches to reduce system weight, size, and cost.

Alternative Chemical High Energy Density Materials - High energy density materials (HEDM) are nominally chemicals that have energetics exceeding hydrogen/oxygen via rapid exothermic decomposition [ref. 14]. Typically, these materials are considered safety issues and consequently the typical technology readiness level (TRL) level of these materials is low. There are three prime uses for HEDM: explosives, batteries, and propulsion. Chemicals which have a

greater energy density than hydrogen/oxygen (15.8 Mj/Kg) include: Octaazacubane (N8, 22.9 Mj/Kg), cubic gauche nitrogen (33 Mj/Kg), lithium plus fluorine (23.75 Mj/Kg), and beryllium plus oxygen (23.9 Mj/Kg). Octaazacubane is considered an explosive, but evidently has not yet been developed as a fuel. Fluorine is extremely corrosive and reactive; beryllium is carcinogenic and a health hazard. These issues have reduced interest in them in spite of the potential increases in Isp of 50% to 100%, values approaching nuclear thermal propulsion levels.
ISRU Fuels - There are a plethora of potential chemical fuels available via ISRU collection and processing. These include Mg/O_2 (Mars has much of both), H_2/O_2 (Mars has much water), CH_4/O_2 (C from Martian atmospheric CO_2), CO/O_2, H_2/CH_4/CO, CH_3OH, and many others.

Separating Propulsive Mass and Energy - Initially, space propulsion, both space access and in space, utilized combustion and expulsion of chemical “fuels” carried on board. These chemicals produced energy and after combustion, constituted the propulsive mass/momentum. The best such chemicals in terms of Isp and force/flow rate that are deemed safe engineering/mission wise, are hydrogen and oxygen, producing some 450 seconds of Isp. There are more reactive chemicals (e.g., fluorine) which have a higher Isp, but these have serious safety issues. Propulsion in atmospheres can injest atmospheric constituents (aka “airbreathing propulsion”) this can provide additional propulsive mass when heated and be a component of the combustion/energy generation process. This utilization of non-stored/carried propulsive mass provides partial separation of propulsive mass and energy and produces higher Isp. The other approach to separating propulsive mass and energy is to supply additional energy. This is done either on board or added from offboard and comes from sources such as nuclear or solar. This is the approach for fission nuclear thermal propulsion, which can provide an Isp in excess of 800 seconds. Other processes than, or in addition to, thermal expansion, such as electro-magnetics, can be employed to increase exit velocity and Isp [refs. 15 and 16].

The key to higher-than-chemical Isp, beyond H_2-O_2, and beyond the radiated energy limitations of solar, is a light weight, high energy density source, either on board or utilization of energy beaming to the vehicle. Propulsive mass can be carried on board, possibly sourced beyond the surface of Earth via ISRU, including harvesting from atmospheres. High Isp via E-M related propulsive mass acceleration requires sufficient ionization and conductivity. The major metrics for space propulsion are costs, safety, Isp, weight, and thrust level. The latter is dependent upon mission requirements - high thrust for human missions to reduce time exposed to radiation and micro g, etc., and high thrust for space access. Costs are reducing via reusability, printing manufacture, and robotization of manufacturing and operation. Chemical rockets provide high thrust from the expansion of the heated mass constituents at high mass flow. The other high-thrust propulsion approach is magnetohydrodynamics, which, in addition to high thrust, has high Isp (over 2,000 seconds). The VASIMIR engine proffers some 6,000 seconds of Isp at high thrust [ref. 17]. Electric propulsion cycles are capable of Isp much higher than that, but at low thrust levels using available energy sources. With cost as a major metric, reusable rockets and improved manufacturing and operations are rapidly greatly lowering the costs of space access, which could provide/supply in space fuel depots and affordable chemical propulsion for the desired human fast transits (e.g., some 200-day round trips to Mars). The other option for fast transits is VASIMIR, given a nuclear on-board energy source that has the requisite many megawatts of power and an alpha, Kgs of weight/KW of energy produced of order one (i.e., a light weight, high energy density energy source).

Potential candidates for propulsive mass can be evaluated from a combination of what mass is available and what mass characteristics are required/useful for the selected propulsion and energy addition systems. The obvious options for propulsive mass utilization include carrying on board ab initio, as is done with current ion engines and nuclear thermal designs, or ingesting from the local atmosphere for real time or later “air-breathing” propulsion. Then there is ISRU mass and volatiles from moons, asteroids, planets, either straight or refined regolith/volatiles. One approach for exoatmosphere if you are leaving an atmosphere is to open an inlet and take on board outer atmosphere constituents. This can be utilized as propulsive mass by using on or off board/beamed energy and with or without alkalines to increase conductivity. This would save much of the cost to lift the mass from the surface. Magnetohydrodynamics and ion/electric propulsion require easily ionized materials such as the alkalines, which are present on Mars, for example. Conventional rockets utilizing expansion of heated materials requires mass that can be heated and produces an acceptable level of Isp [ref. 18].

Electrostatics - In the Earth's atmosphere, due to solar wind and lightning there is some 100 direct current (DC) volts per meter near the surface, and nearly a million volts between the surface and the ionosphere. In West Virginia, a tower was erected and produced electrical DC energy to operate a one tenth horsepower motor continuously. On Mars, due to the dust storms, there is some 500 volts per meter near the surface. DC motors are more efficient than alternating current (AC). Venus' upper atmosphere is extremely ionized by solar wind and tribo-electric activity of thick atmospheric gas.

Energy Regeneration - All energetics systems have losses, the amplitude of which is a function of specific design details, with the losses usually occurring as heat. This heat is normally dissipated using radiators, heat exchangers, cooling towers, etc. In the design of many systems, there have been efforts to regenerate energy and reuse these losses, notably in auto braking, trains, wind turbines, elevators, buses, cranes, robotics, power plants, photo voltaics, fuel cells, etc. [ref. 19]. The components of an energy regeneration system include energy extraction, transmission, storage (depending upon the details of the reuse approach), conversion, control and finally utilization.

In space faring systems, weight is always a serious issue (metric). Many to most current space systems do not employ regeneration, leading to larger sized/weight/cost energy generation and heat dissipation systems. Regeneration is an option to enable these system components to be smaller/lighter/less expensive with the systems tradeoffs being the added weight/cost and size of the requisite regeneration components. Particular space energetics related systems with potential regeneration net favorable impacts include nuclear reactors, batteries, photovoltaics [PV], lasers, and others that generate heat that has to be dissipated (which in space means radiation to space).

Approaches to optimize regeneration and energy generation/loss dissipation include:

For Generation:

- Nuclear batteries, alpha, Kgs/Kw of order 1, huge weight savings; they scale from the very small to many megawatts
- Frontier PV with two electrons per photon and utilizing much more of the solar spectrum, efficiency approaching 70% plus projected

For Dissipation:

- Heat exchangers with riblet surfaces, greater heat transfer per unit of pumping power [ref. 20]
- Liquid droplet radiators/belt radiators, major size/weight reductions [ref. 21]

For Conversion:

- High efficiency T-E
- High efficiency T-PV
- High efficiency Thermionics

For Storage:

- Frontier, eventually lithium-O_2 batteries, up to 8X Li-ion
- Structural ultra-caps and heat batteries

What is apparently needed are systems studies of various combinations of regenerative system piece parts for one or several onboard, on body energetics sources/ utilizations that might benefit from regeneration, be potentially downsized, including energy source and radiator size with the metrics of overall cost, safety, reliability, size, weight. This to determine the efficacy, benefits of increased utilization of regeneration.

Energy Conversion - Optimal utilization of power and energy usually requires energy conversion processes, wherein energy is converted from one form to another more useful form. The most common conversion desired is heat into electricity such as for nuclear fission reactors, which produce heat, requiring for most applications conversion into electricity. As discussed herein, there are many extant conversion approaches. Which approach is most efficacious for a given combination of generation approach and usage is a system and system of systems level optimization issue that takes into consideration cost, weight, size, efficiency, robustness, temperature levels, materials, and safety. The extant energy conversion options for space applications with their peak level efficiency include [ref. 22]:

- Thermal Electrics, utilizing spatial temperature gradients, with 5% to 20% efficiency
- Piezo-Electrics, utilizing mechanical movements; heat is not directly involved so efficiency is up to 80%
- Thermal Photovoltaics, utilizing radiated IR, up to 60% efficiency
- Pyro-Electrics, utilizing temporal temperature changes, up to 90% of Carnot efficiency
- Thermodynamic Cycles, such as Sterling or Brayton, utilizing turbine rotation to turn electric generators, 40% efficiency
- Fuel Cells, convert chemical energy to electricity, 80% efficient
- Solar Cells/Photovoltaics, convert photons to electricity, efficiency to 50%

Higher overall system conversion efficiencies have been operationally obtained by combining several conversion processes. These conversion approaches are utilized for energy regeneration as well as for primary usage. All of these conversion approaches have individual optimization conditions, all are subjects of ongoing research and systems optimization, recipients of benefits from ongoing miniaturization and materials technologies, and are applied across the spectrum of non-aerospace domestic and industrial requirements. Particularly interesting current research developments in energy conversion include for PV, two electrons per photon and utilization of much more of the incident photon spectrum, positing efficiencies up to 70%. Then there is the Sang Choi invention of a new approach to T-E conversion, with efficiencies above 20%.

Energy Storage - Energy storage in space faring is required for applications of solar energy when/where the Sun is not always available, and for on planet habs, transportation, ISRU, and space suits. The nuclear batteries scale nicely and are fundamentally a storage device. Some storage approaches have sufficient capacity to power some ISRU processes (e.g., chemical fuels and nuclear batteries). A summary of the energy storage approaches includes:

- Capacitors, for short, high power requirements, can be made integral to the vehicle/device structure
- Electrical batteries writ large, chemical and nuclear

- Heat batteries, heat storage in chemicals, molten salt, requires energy conversion to electricity
- Chemical including ISRU sourced fuels, fuel cells or thermodynamic cycles used as conversion device for electricity
- Osmotic fluids, a combination of clear and salty fluids that, when mixed, produce electricity; fluids can (via heat/evaporation) be regenerated back into an energy storage mode

As with energy regeneration, which is intertwined via systems with storage and production, the particular storage, or set of storage approaches used for a particular application, is a systems level optimization for cost, size, weight, capacity, temperature/radiation, robustness and safety. The breakthrough for storage that will massively alter essentially all aspects of space faring power and energy, including propulsion, in space and on planet habs, on planet transportation, ISRU, just about any energy utilization in space, are the new nuclear batteries. These batteries are very energy/power dense, far better than reactors. They have the capability to scale from powering phones to tens of megawatts for in space propulsion of Vasimir, which with 6,000 secs of Isp and high thrust, proffers fast round trips to Mars, fast enough to greatly alleviate radiation issues.

Photovoltaics - Except for missions to the outer planets where solar energy becomes very weak, most of spacefaring thus far has utilized solar energy , usually acquired via photovoltaics. The sun does not set in space and it is cloud free, so the intensity and solar exposure time is much greater in space than on Earth. Most are familiar with photographs of the huge PV arrays attached to the ISS. Solar voltaic arrays are a major cost and weight issue, but there are many approaches not yet utilized to reduce their cost and weight. The Energy Regeneration section described some of these approaches, which are at the systems level. There are large radiators to dissipate the waste heat from the PV cells. There are far more efficient radiator designs/approaches [ref. 21] that would reduce the weight/cost of the requisite PV radiators. In addition there are also regeneration possibilities for the heat before it gets to the radiators, reducing their size and weight much further. The regenerated energy would increase the efficiency of the overall system and reduce the size, weight, and cost of the PV fields. All of this needs to be system of systems optimized to include the costs/weights of the regeneration system(s) to determine the resultant benefits. On body day/night cycles require solar storage or other energy sources at night.

The other major source of potential major improvements in the PV fields is projected increases in the efficiency of the PV itself. There are several research level results including two electrons per photon and utilizing more of the solar spectrum and other systems level approaches which are posited to increase the efficiency of the PV cells to 70% [refs 23 – 25]. This again would reduce the size of the PV acreage required, reduce the amount of waste heat and the size/weight of the radiator. There is also progress in developing PV for IR to harvest planetary/body energy radiation.

Nuclear Batteries - Recent invention of nuclear batteries with up to orders of magnitude greater energy density and much reduced overall weight (alpha down to order one, up to 22 KWs/kg of isotope vice usual 20 Watts/kg) which last for years, opens up an entirely different in-space transportation and surface mobility trade space [e.g., ref 3]. The NASA version is the quantum energetic process based Nuclear Thermionic Avalanche Cell (NTAC), which releases a large number of intra-band or inner shell electrons via utilizing high energy photons of 100 keV to MeV. The design scales from powering phones to tens of megawatts, with the far longer-term operability expected of nuclear vs. chemical batteries. The new nuclear battery designs could power nearly everything in space including in-space and on body habs, ISRU, and on-body and in-space transportation. Estimates indicate they could power VASIMIR, a high thrust MHD propulsion system with an Isp of 6,000 seconds. This could enable a 200-day round trip to Mars, which would greatly alleviate in-space radiation and micro g health concerns. Other potential utilization includes powering satellites, terrestrial and deep space mining, ships, manufacturing, and utilize nuclear fission waste as fuel, generate electricity, and reduce the radioactivity in the process. For on-surface transportation, there are three obvious possibilities to utilize this new nuclear capability: lower speed, nuclear ramjets, and nuclear rockets. On Mars, such a nuclear battery could supply propulsive lift for long haul, as well as short haul via intaking CO_2 from the atmosphere and pressurizing it via electric motors turning axial flow compressors which is exhausted downwards using ejector nozzles to provide lift and thrust. For higher speeds up to high supersonics, the new nuclear batteries could either power heating and additional compression for an atmospheric ramjet or heating for a conventional rocket, with or without addition of chemical energy using on-planet ISRU derived propellant or propulsive mass. There are a multitude of ISRU applications for such nuclear batteries, especially for autonomous and lunar night operations. Electrolysis of ice into hydrogen propellant and oxidizer to enable a lunar economy or for return fuel from Mars requires far more power than current technologies can deliver (except much larger and more expensive nuclear reactors). Projections of full-scale performance suggest that the new nuclear batteries can provide essentially all on body/planet energy requirements, including those that require portability.

Space Solar Power

NASA initiated and conducted R&D activities in power beaming technology (PBT) starting from the late 1970s to date. The in-space collection can be via either PV or solar thermal, beaming via lasers or microwaves, and collection occurs on-body via rectennas. This solar approach can provide distributed power at overall levels and under conditions not feasible - to - possible with on body solar systems. Optimization approaches previously cited can apply to space solar power systems. The decreasing costs and tighter beam delivery are making laser-based systems increasingly feasible.

Advanced Thermo-Electrics

Most of the power systems considered herein produce a large amount of heat as waste, some 60% of their energy output. Recovery and conversion of the waste heat into electrical power as noted in the previous energy conversion section provides additional useful power to the system and reduces the size and weight of thermal radiation panels. Thermoelectric (TE) devices are commonly used to recover and convert thermal energy into electrical power. However, current semiconductor TEs have intrinsic Brillouin limits on mobile electrons within phase space which is dictated by mainly n-type and p-type dopant densities. Therefore, the maximum achievable efficiency of such TEs is approximately 6~7 %. Limits on electron mobility also constricts heat flow carried by energetic electrons. In semiconductor TEs, the TE developers alter the lattice oscillatory (phonon) transmission in TE materials to increase the figure of merit performance. This practice itself also constricts the overall heat flow into a TE domain, which lowers the energy to be converted. A new TE concept based on metallic junction TE (MJ-TE) was developed at NASA LaRC [refs. 26, 27]. A simulation analysis of MJ-TE shows very promising performance with 20% efficiency.

Farther Term

LENR - Revived (after experiments earlier in the 1900s) in the late 1980s [ref. 28] and dubbed “Cold Fusion,” what is now usually termed LENR (Low Energy Nuclear Reactions) was an experimental discovery with replication issues at the time and lacked an acceptable theory. Now, three decades of extant worldwide experiments [ref. 29] indicate “something nuclear” is real. However, there does not yet exist a cogent, verified theory and therefore LENR has been looked at with askance by the physics community. There are now extant recent weak force and other weak neutron-based theories (not “hot” fusion) involving surface plasmons, electroweak interactions explicable via QED on surfaces, collective effects, heavy electrons, ultraweak neutrons, and utilizing neutron generation to obviate coulomb barrier issues. There are now many patents and LENR is beginning to evolve into the marketplace. Given a validated theory to engineer, scale, and make safe, LENR would obviously be a major world energy revolution, especially with observed energy density levels surpassing those of chemical energy. In fact, LENR has been observed in the tens to hundreds and theoretical possibilities into the many thousands times chemical energy density levels. In the Widom-Larsen Theory [ref. 30], H_2 is adsorbed or “loaded” onto a metal surface and the resulting surface plasmon initiates collective effects. Some energy is added and several types of energy appear to work. From the LENR experiments and a sizable body of applicable related research, nano cracks/asperities in the surface morphology concentrate energy over an area and produce high localized voltage gradients. Such voltage gradients excite collective electrons to combine with protons in the surface plasmon to form ultraweak neutrons. These neutrons readily interact, producing neutron rich isotopes which undergo beta decay and transmutations. The heavy electron cloud converts the beta decay to heat, sans worrisome radiation and coulomb barrier issues, in agreement with experiment(s).

From experiments thus far, surface materials are required that adsorb large amounts of hydrogen (H_2 or D_2) such as Ni, Palladium, etc. Once operating, internal IR appears to be capable of replacing the input energy. The LENR process occurs at surfaces or at nano morphology sites. Generic LENR “products” from experiments include heat, transmutations, and possibly some radiation, especially during startup or shutdown where there may be incomplete coverage of heavy electrons to accomplish conversion to heat (an engineering issue). Also, transmutation products can include helium four and tritium. The three decades of experiments, lacking theoretical guidance, produced mostly low levels of heat. A few studies produced up to KWs. Several experienced runaway when they evidently got it more right, which may be a greater morphological population of nano scale sites. When such occurred, sometimes windows were melted, fires occurred, even an explosion or two. The experiments are now reproducible. From three decades of many hundreds of, in many cases very detailed and careful experiments with redundant measurement approaches, positive results occurred over a relatively wide range of conditions/materials and energy input approaches.

LENR is apparently a non-obvious multistage process involving the weak force. Initial claims of “cold fusion” poisoned the well and became the energetics third rail. There was also lack of validated physics understanding and usually only low heat levels produced. There was also a dearth of experiments focused on validating theory (or not), mostly variations on previous experiments vice the basic physics and efforts to identify such. It was often considered simply too good to be true…incredulity. There were observations, beginning in the 1600s, and still ongoing, of transmutations including silicon, carbon, magnesium, potassium into calcium, and many others in biological systems. Experiments, many carefully done, were conducted before the late 1980s primarily in France, Germany, and Russia. These cited transmutations observed occurring in plants, seeds, bacteria, microorganisms, and mammals. An oft cited instantiation is the calcium shell on chicken eggs. If calcium is withheld in the diet, apparently mica and potassium are transmutated. If these are absent, there are no shells. This occurs with no observed heat or radiation. From refs 31 and 32, the LENR effect has been replicated hundreds of times while using different materials and five different methods of energy addition. Each method is found to produce energy well in excess of any plausible chemical source and that is correlated with identified nuclear products. LENR patent holders include: Airbus, Google, Leonardo, Brillouin, Mitsubishi Heavy Industries, Widom-Larsen, Boeing, MIT, and the U.S.

Navy. LENR produces heat, which can be utilized directly or converted to electricity via such as Sterling Cycles, Thermoelectrics, Pyroelectrics, T-PV, Etc.

Recent research in Japan via long and careful experimentation, has proven that a major “missing controlled parameter” in the decades now of previous LENR research is the requirement for nano sized discrete surface morphology. As already noted, that enables localized energy concentration by orders of magnitude. Major organizations (including Google) are now conducting research aimed at understanding and sorting out sensitivities and optimization. The major issues going forward include development of a viable, proven theory to allow engineering, scaling, and safety. Given that, which at this point appears to be a work in progress, much with regard to power and energy could change, for climate/transportation/HVAC, energy costs overall, and in-space for propulsion, habs, ISRU, on body transportation.

Nuclear Isomers - Metastable Nuclear Isomers are exited states of nuclei that emit gamma radiation when de-excited. The emitted energy is stored in the excited state as shape or spin changes, with an energy density of emitted gamma energy on the order of E5 times chemical energy density, which is less than the E6 to E7 of fission/fusion. The half-life of these excited states vary from very short to extremely long. There are more than 100 isomers with a half-life greater than a week. The usual/natural decay rate for isomers provides some modicum of energy via utilization of the gamma energy as a heat source. However, the engineering opportunity and challenge is to trigger serious gamma release as a function of energy load and requirements. Therefore from a space operations standpoint, isomers could conceivably constitute an almost fission level controllable nuclear battery. There are three major issues/problems/difficulties with isomer powered nuclear batteries: 1. The costs of production of the isomeric state, 2. affordable, effective, and controllable means to trigger the gamma release at the time and rate desired with a useful net positive energy production, and 3. systems engineering level viable protection from gamma radiation at high Kev to low Mev levels. All of these issues are under active study but at the present time the isomer approach for space power and energy is at a very early research stage [refs. 33 and 34].

Positrons - Positrons are positive electrons and are the affordable anti-matter. Medical pet scans utilize positrons. When they annihilate with an electron, producing two 511 Kev gamma rays, there is essentially a 100% mass to energy conversion. Therefore, their energy density is some E9 times chemical, order(s) of magnitude more than fission/fusion which involve fractional mass-energy conversion. There is no radioactive residue. This is the highest energy density source known and it can be produced in accelerators, with beta decay, and other methods/phenomena, including laser irradiation. The gamma produced can be used to heat tungsten, other materials, and can be converted to heat for propulsion or employed directly for electricity production via photoelectronics. The major issue with utilization of positrons for space power and energy is positron storage. Storage approaches have included Penning traps and as positronium and are an active area of research. Storage times on the order of 1,000 minutes have been mentioned with projections for storage duration exceeding a year. The alternative to storage is to use suitable isotopes and generate positrons as needed, which is the approach for medical pet scans. Studies of positron powered thermal rockets indicate Isp levels of 1,000, a bit greater than fission nuclear rockets at possibly reduced Kg/Kw (alpha) [ref. 35].

Atomic Fuels - Recombination of atomic species is a mono-propellant, with an energy density order of 20 times chemical. Storage of, for example, H (not H_2) is possible either as metallic hydrogen or embedded in solid hydrogen (molecular hydrogen at four degrees K). This provides a potential Isp for thermal rockets in the range of 1200 seconds. If utilized with an oxidizer, the Isp is reduced. Atomic boron and carbon provides Isp in the range of 700 seconds [refs. 36,37].

SBER - SBER is shorthand for Structural Bond Energy Release. It was discovered originally by Bridgeman when he used a combination of shear and compression enabled sugar and other hard to combust materials causing them to explode. The Gilman theory, Mechanochemistry, provides an explanation of the effects of shear and compression which is the collapsing of electronic band gaps. Engineering effects of such material processing includes cold, orders of magnitude more rapid, chemistry, utilization as an initiator to combust materials not usually consider combustible (a superb “spark plug”) and energy storage. Research tasks to operationalize such capabilities include stabilization of treated processed materials at ambient conditions and ensuring efficacious activation. It is of interest that application of shear and compression produces, via collapsing band gaps, E-M emissions which can be employed as NDE to detect cracking and earthquakes. SBER effects can be produced using lasers and sufficient processing can produce gamma and other radiation to possibly trigger nuclear processes [ref. 38].

Fusion - For many decades now, fusion energy has been an unrealized energetics vision with regard to power and energy writ large including space applications, especially propulsion, for which there exist a plethora of designs and alternatives. Compared to fission energy, fusion is much more difficult to achieve. How difficult is a function of the “fuels” employed. Also, fusion can have a somewhat greater energy density, different, and usually lower radioactivity hazards, and requires less expensive and more abundant fuel. A plethora of approaches and fuel combinations have been conceptualized and studied over the years, including multitudinous fusion powered rocket designs. Thus far, fusion has not successfully produced a net positive energy output, even for terrestrial power where weight is not the serious issue it is in space. Anti-matter/positron power and energy is farther along than fusion and has orders of magnitude greater energy density. Currently, there are many “mini” fusion concepts under study. Some of these utilize highly densified deuterium, which itself requires far more study. However, if is as suitable as envisaged, densified deuterium would greatly reduce the difficulty of establishing the conditions for fusion to occur. Key fusion space power and energy development issues include establishing and stabilizing the requisite conditions long enough for fusion to occur, energy conversion, radiation related safety, and overall weight and efficiency/useful net positive energy [refs. 39, 40].

Sails – Sailing propulsion is possible using photon sails (solar, laser driven), magnetic sails (working off of the particles in the solar wind, a loop of wire/CNTs, etc.), and particle impact sails (propel particles including using mass drivers, etc. into the sail). Sails are under development for space propulsion and are being considered for supply transports, which can be slower than the transport of humans.

Concluding Remarks

Power and energy are the foremost keys to affordable and safe space faring. The current power/energy approaches for space include solar, chemical including via ISRU, nuclear fission reactors, and RTGs. Solar can be improved by regeneration of heat losses, use of multiphase radiators, several approaches to greatly improve efficiency, and also structural energy storage. However, the current technologies in fission and solar do not offer the high-density portable power systems necessary to conduct key ISRU tasks such as ice mining and propellant production, additive manufacturing and surface construction on the Moon and Mars, and fast transits to/from Mars for maintaining crew health.

There are in development nuclear batteries that are orders of magnitude lighter than reactors, scale from milliwatts to megawatts, have energy density up to 22 Kws/Kg of isotope which could power essentially everything space-related including propulsion and habs both in-space and on-body, ISRU, and manufacturing. Such batteries could provide 200-day Mars round trips.

Storage of positrons, with energy density 2 orders of magnitude greater than fission/fusion has been demonstrated. This is the greatest energy density available and the radiation of .5 Mev gamma is prompt with no residual.

As non-chemical sources at high power and energy levels become available, propulsive mass and energy can be separated, vice use of a fuel that provides both. Utilization of approaches to increase conductivity enables use of non-chemical energy sources of matter as propulsive mass, including possibly regolith.

If the physics of LENR can be developed, it would allow optimization, scaling, and safety, providing yet another candidate for a power and energy revolution with application to space faring.

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14. ABSTRACT

Report reviews, summarizes and projects the frontiers of space power and energy across the spectrum of deep space, beyond GEO, requirements. The recent developments in high energy density, lightweight, scalable nuclear batteries provides an alternative going forward to nuclear reactors and chemical fuels for requirements from propulsion to habitats/spacecraft, ISRU and on body transportation. There are several interesting farther term powewr and energy sources including positrons, the highest energy density souce known. Also important will be energy regenewration and multiphase space radiators.

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