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Separating Propulsive Mass and Energy for Space Applications

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INTRODUCTION

Initially and traditionally, space access and in-space propulsion utilized combustion and expulsion of chemical "fuels" carried on board, with performance governed by the rocket equation. These chemicals produced energy, and after combustion, constituted the propulsive mass/momentum. The best such chemicals in terms of Isp that are deemed safe engineering/mission wise are hydrogen and oxygen, producing some 450 seconds of Isp. There are more reactive chemicals, such as fluorine, which have higher Isp, but also have serious safety issues. Propulsion in atmospheres can ingest atmospheric constituents (aka "airbreathing propulsion") which provide additional propulsive mass when heated and 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, either on board or added from offboard, supply additional energy, such as from nuclear or solar sources. This is the approach for fission nuclear thermal and electric propulsion, which can provide an Isp in excess of 800 seconds of Isp. Other processes or in addition to thermal expansion, such as electro-magnetics, can be employed to increase exit velocity and Isp [refs. 1 and 2]. Separating propulsive mass and energy for space faring is commonly referred to as a means to circumvent the rocket equation and is capable of producing major benefits for the development of commercial deep space and space faring in general including affordable fast transits to mitigate the human health impacts of galactic cosmic radiation (GCR) and microG.

The key to higher than chemical Isp, beyond H_2-O_2, and beyond the radiated energy and systems limitations of solar for space faring, is a light weight, high energy density source, either on board or via utilization of energy beaming to the vehicle. Traditional energy sources include chemical, heat, electrics, mechanical, photons, and nuclear. Propulsive mass can be carried on board, sourced beyond the surface of Earth via in-situ resource utilization (ISRU), and includes harvesting from atmospheres. High Isp via electromagnetic 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 dependent upon mission requirements. High thrust for human missions is needed to reduce time exposed to radiation and microG and high thrust is required for space access. Costs of space access 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 (MHD), which, in addition to high thrust, has a high Isp of over 2,000 seconds of Isp. The VASIMIR engine offers some 5,000 seconds of Isp at high thrust [ref. 3]. 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, on the order of one (i.e., a light weight, high energy density energy source).

The purpose of this report is to examine the options beyond traditional rocket engines, where propulsive mass and energy are combined, specifically the separation of propulsive mass and energy. This report considers the spectrum of advanced energetics, sources of propulsive mass, conductivity enhancement approaches, energy beaming possibilities, and candidate propulsion cycles. Suggestions are made for various combinatorial, system level, beyond traditional combustion rocket, space propulsion approaches for human deep space missions given the changing conditions of increased knowledge of deep space resources for ISRU, revolutionary energetics, and technology advancements writ large.

ADVANCED SPACE ENERGETICS

Energy Regeneration And Conversion [ref. 25]

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. The components of an energy regeneration system include energy extraction, transmission, and, depending upon the details of the reuse approach, storage, conversion, power management, and finally utilization.

In space faring, systems weight is always a serious issue and metric. Many to most current space systems do not employ regeneration, leading to larger size/weight/cost energy generation and heat dissipation systems. These system components could possibly 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 (when in space, this means radiation to space).

Approaches to Optimize Regeneration and Energy Generation/Loss Dissipation Include:
For Generation - Advanced nuclear batteries, with an alpha of order one, vice reactors with alpha in the 20s to 100s, a huge weight saving; they can also scale from very small to many megawatts. Also, frontier PV with two electrons per photon and utilizing much more of the solar spectrum, with projected efficiency approaching 70%.

For Dissipation - Heat exchangers with riblet surfaces with greater heat transfer per unit of pumping power and liquid droplet radiators/belt radiators with major size/weight reductions [ref. 4]

For Conversion - High efficiency T-E, high efficiency T-PV, high efficiency thermionics

For Storage - Eventually lithium-O_2 batteries, some 8x Li-ion or heat batteries, and structural batteries

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

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. These reactors produce heat, requiring for many applications conversion into electricity. There are many extant conversion approaches that are most efficacious for a given combination of generation approaches and usage. The extant energy conversion options for space applications with their nominal peak efficiency include [ref. 5]:

- Thermal electrics, utilizing spatial temperature gradients, 5% to 20% efficiency
- Piezo electrics, utilizing mechanical movements, heat is not directly involved, efficiency up to 80%
- Thermal photovoltaics, utilizing radiated IR, to 60% efficiency
- Pyroelectrics, utilizing temporal temperature changes, up to 90% of Carnot efficiency
- Thermodynamic cycles, such as Sterling or Brayton, utilizing 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 system conversion efficiencies can and have been operationally obtained by combining several conversion processes in series. These conversion approaches are utilized in energy regeneration as well as for primary usage. All of these conversion approaches have particularly efficacious application specifics, are subjects of ongoing research and optimization, are recipients of benefits from ongoing miniaturization and materials technologies, and are applied across the spectrum of non-aerospace domestic and industrial requirement.

Energy Storage

Energy storage in space faring is required for applications of solar energy when/where/if the Sun is not always available, and for on-planet transportation and space suits. The NTAC advanced nuclear battery [ref. 6] scales nicely down to transportation utilization and could be considered a storage device in space as a replacement for a chemical battery. Some storage approaches have sufficient capacity to power some ISRU processes (e.g., chemical fuels and NTAC.) A summary of the energy storage approaches includes:

- Capacitors for short and high-power requirements can, going forward, be made integral to the vehicle/device structure.
- Electrical batteries such as chemical and nuclear, lithium/O_2 chemical batteries could approach chemical energy density.
- Heat batteries, heat storage in chemicals, and molten salt, require energy conversion to electricity
- Chemical including ISRU sourced fuels, fuel cells, or sterling cycle used as conversion device for electricity
- Osmotic fluids, a combination of clear and salty fluids that, when mixed, produce electricity. The fluids can, via heat/evaporation be regenerated back into an energy storage mode

As with energy regeneration, which can be 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 in storage that will massively alter all aspects of space faring power and energy (including propulsion in space and on planet habitats, on planet transportation, ISRU, etc.) and just about any energy utilization in space, is an NTAC class nuclear battery. This battery design is very energy/power dense at far less weight than reactors, yet scales from powering phones to tens of megawatts for in space propulsion of VASIMIR.

Fission Reactors

Thus far, 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 1960s, Russia launched the TOPAZ small fission reactor, 10 kWe, using thermionic conversion. The U.S. launched the SNAP 10 (A) in the 1960s and in the 1980s started development of the SNAP 100. Unfortunately, that project was canceled before flight. More recently in the U.S. several micro nukes have been studied, including Rapid-L and AMTEC with the most recent one, Kilo power, on a development path for utilization on the Moon [ref. 7]. There are several notable benefits of fission reactors, the most important of which is years of high power output. Before the invention of advanced nuclear batteries, 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 in regard to human missions), major size and weight driven by radiation protection and energy conversion, and protection from crushing, fires, impact, and explosions. There are ongoing efforts which auger reduced size, weight, and improved safety. There is a plethora, worldwide, of small/miniature reactor designs, traveling wave reactors, and a Russian vortex pebble bed design with greatly improved power density. Going forward and given the need for human missions of 24/7/365 availability of high-power levels for habitats and the power requirements of ISRU, fission reactors, supplanted or supplemented by advanced nuclear batteries, will be a mainstay of Moon, Mars and beyond human exploration, exploitation, and colonization. All nuclear and other power generation development should consider advanced radiator and energy regeneration approaches to reduce system weight, size, and cost [ref. 8].

Photovoltaics

Except for missions to the outer planets where solar energy becomes very weak, most of spacefaring thus far has utilized solar energy which is 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 the huge PV arrays associated with the International Space Station (ISS). Photo-voltaic arrays are a major cost and weight issue. However, there are many approaches not yet utilized thus far (perhaps because of low TRL) to reduce their cost and weight. The regeneration section described some of these approaches which are at the systems level. There are currently large radiators to dissipate the waste heat from the PV cells. More efficient radiator designs/approaches would reduce the weight/cost of the requisite PV radiators, as might regeneration possibilities for the heat before it gets to the radiators, reducing their size and weight 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 system of systems optimization.

The other major source of potential major improvements in PV are projected increases in the efficiency of the PV itself. This would reduce the size of the PV acreage required, reduce the amount of waste heat, and the size/weight of radiator required. There is also progress in developing PV for IR to harvest radiation energy from planetary/other bodies. Then there are solar concentrators aided by the technology advances in lightweight membranes.

LENR [ref. 25]

In the late 1980s, LENR (Low Energy Nuclear Reactions) (originally "cold fusion") was revived after experiments earlier in the 1900s [ref. 9]. It was an experimental discovery with replication issues at the time and lacked an acceptable theory. Now, three decades of extant worldwide experiments [ref. 10] indicate "something nuclear" appears to be happening. However, a verified theory does not yet exist and therefore LENR has been looked at with askance by the physics community. There are weak force and weak neutron-based theories (not "hot" Fusion) involving surface plasmons, electroweak interactions explicable via QED on surfaces, collective effects, heavy electrons, ultraweak neutrons, utilizing neutron generation to obviate coulomb barrier issues. There are many patents and several books written around LENR. Given a validated theory to engineer, scale, and make LENR safe, there is the possibility that it could become useful in space. Thus far, observed energy density levels as multiples of chemicals observed in experiments are in the tens to hundreds with theoretical possibilities into the many thousands.

In the Widom-Larsen Theory [ref. 11], 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 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 an ultraweak neutron. 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 absorb large amounts of hydrogen (H_2 or D_2) such as Ni or palladium. Once operating, internal IR may 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, and some evidently experienced runaway heating which may have been due to a greater morphological population of nano scale sites. The experiments are now reproducible. There are three decades of very detailed, careful experiments with redundant measurement approaches and positive results 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 LENR became the energetics "third rail". There was also lack of validated physics understanding, usually only low heat levels produced, and a dearth of experiments focused on validating theory (or not). These extant experiments are mostly variations on previous experiments vice addressing the basic physics and efforts to identify such.

From refs. 12 and 13, 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 often 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.

Nuclear Isomers [ref. 25]

Metastable nuclear isomers are exited states of the nucleus 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 which involve changes in the nucleus. The half-life of these excited states varies 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 emitted gamma energy as a heat source. 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, or difficulties with isomer powered nuke batteries: the costs of production of the isomeric state, affordable, effective, and controllable means to trigger the gamma release at the time and rate desired with a useful net positive energy production, and systems engineering level viable protection from the 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. 14 and 15].

Positrons [ref. 25]

Positrons are positive electrons and are the affordable anti-matter. Medical pet scans utilize positrons. When they annihilate with an electron, they produce two 511 keV gamma rays and there is essentially a 100% mass to energy conversion. Therefore, their energy density is some E9 times chemical and order(s) of magnitude more than fission/fusion, which involve fractional mass-energy conversion. There is no radioactive residue. It has the highest energy density source known and can be produced in accelerators, beta decay, and other methods/phenomena, including laser irradiation. The gamma produced can be used to heat tungsten, other materials (i.e., 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 is an active area of research. Storage times on the order of 1000 minutes have been mentioned with projections for storage duration exceeding a year. The alternative to storage is to generate positrons as needed (using suitable isotopes), 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 thermal nuclear rockets at possibly reduced kg/kW (Alpha) [ref. 16].

Atomic Fuels [ref. 25]

Recombination of atomic species is a monopropellant, with an energy density order of 20 times chemical. For example, storage of H (not H_2) is possible either as metallic hydrogen or embedded in solid hydrogen (molecular hydrogen at 4 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 provide Isp in the range of 700 sec. [refs. 17 and 18].

SBER [ref. 25]

SBER is shorthand for Structural Bond Energy Release. Discovered originally by Bridgeman who, using a combination of shear and compression, produced explosions in sugar and other hard to combust materials. The Gilman theory, Mechanochemistry, provides an explanation of the effects of shear and compression – collapsing electronic band gaps. Engineering effects of such material processing includes cold and orders of magnitude more rapid chemistry and 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 that 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 19].

Fusion [ref. 25]

For many decades now, fusion energy has been an unrealized energetics vision in regard to power and energy as a whole including space applications (especially propulsion) and for which there exist a plethora of designs and alternatives. Compared to fission energy, fusion is much more difficult to achieve, and 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 utilize a less expensive and more abundant fuel than fission. 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 it is as suitable as envisaged, 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 with useful net energy release, energy conversion, radiation related safety, and overall weight and efficiency/useful net positive energy, as well as cost. [refs. 20 and 21].

PROPULSION UTILIZING SEPARATE PROPULSIVE MASS

Given a selected and developed suitable energy source system, potential candidates for propulsive mass for spacefaring 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 current options for separate propulsive mass include carrying on board ab initio (e.g., nuclear thermal designs) or ingesting from the local atmosphere for real time or later "air-breathing" propulsion. Then there are ISRU mass and volatiles from moons, asteroids and planets (either straight or refined). Martian resources as an example include nickel, titanium, iron, sulfur, magnesium, calcium, phosphorus, chlorine, bromine, aluminum, silicon, oxygen, hydrogen, carbon, nitrogen, sodium, manganese, potassium, chromium, deuterium, aluminum, lithium, cobalt, copper, zinc, niobium, and tungsten. There is a serious need for detailed knowledge of the location(s), nature and extent of such resources. One approach for exoatmosphere if you are leaving an atmosphere is to open an inlet and take on board outer atmosphere constituents which then, using an onboard or off board/beamed energy source and with or without alkalines to increase conductivity, can be utilized as propulsive mass. This would save much of the system cost to lift the mass from the surface. MHD and ion/electric propulsion requires 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 produce an acceptable level of Isp [ref. 22].

Electrical Conductivity Enhancement

As stated, MHD and ion/electric propulsion requires an ionized or electrically conductive fluid to accelerate/produce efficient thrust. The simplest approach to improve ionization is to add energy. An alternative approach is to use propulsive mass additions that are easily ionized, such as alkali metals, which are present on Mars. Then there are electric field strength increases and discharges to incite ionization as well as photoionization. Innate conductivity of regolith depends on the amount of moisture, concentration of ionic species, and the distribution and geometry of pores.

Energy Beaming

The alternative to carrying an energy source on board is to beam the energy to the spacecraft via lasers or microwaves. This is termed "Power Beaming". Historically, lasers with their higher frequency had much less beam divergence than microwaves but were in general more expensive and inefficient. Lasers are usually received on board using PV for electric propulsion. Microwaves have high divergence, were historically relatively inexpensive and more efficient than lasers, and received onboard using rectennas for electric propulsion. Now, lasers have increased efficiency and reduced cost to where the two approaches are similar in cost and efficiency. Membrane optical concentrators and antennas could be used to collect more of the beamed energy and there is some interest in terahertz beaming. There are several ways to reduce mean divergence, including beam profiles such as Bessel, Bowtie, Mathieu, and Airy. Then there are solitons which would also reduce divergence [ref. 23]. Power beaming at substantial power levels has been seriously studied in connection with space solar power (SSP) to transmit the collected solar energy to Earth. Thus far, due the massive cost reduction for renewable energy over these last years, SSP has not been cost competitive.

SYSTEMS APPLICATIONS - SEPARATING PROPULSIVE MASS AND ENERGY

Airbreathers – Airbreathing produces high thrust and Isp, the energy source is the combustion of ingested atmospheric constituents with a fuel, propulsive mass is a combination of combustion products, heated non-combusted atmospheric constituents and unburned fuel. Airbreathing to orbit has the systems level issues of greater dry mass due to need for several propulsion systems, low thrust-to-weight necessitating greater heat load and heat protection weight and lack of ground facilities with resultant cost of many flight tests. "Air" (actually CO_2) breathing for Mars, enabled by the advanced nuclear batteries, appears to be efficacious for on planet transport.

Ion engines – Electrostatic acceleration, high Isp, thrust is a function of applied power, energy source is solar or nuclear or beamed energy, propulsive mass is ionized xenon gas (typical), ionization is a requisite. Field emission propulsion employs cesium or indium as propellant mass.

Plasma/electromagnetic/magnetoplasmadynamic – Lorentz force propulsion, high thrust and Isp, energy source is nuclear or solar or beamed energy, propulsive mass can include argon, CO_2, xenon, hydrogen, lithium, and krypton; ionization is a requisite, conductivity enhancement an option.

Separate thermal energy (nuclear, solar, beamed energy) - High thrust, moderate Isp, propulsive mass is hydrogen for higher Isp, other propellants studied including water and ammonia.

Anti-matter, including positrons and rockets – Similar to thermal, ion, or electromagnetic propulsion, utilizing the E9 times chemical energy density of anti-matter. Positrons are the inexpensive antimatter, provide complete mass to energy conversion with no residual radiation, can now be stored.

ALTERNATIVE CONCEPTS

An example instantiation of the separation of propulsive mass and energy for planets with atmospheres is a systems-level approach. This would obviate most of the huge percentage of the Human-Mars up-mass which is fuel. A rocket is sent to low Earth orbit (LEO) and arrives with an empty tank. The rocket is de-orbited slightly and an inlet is opened to ingest far outer region atmospheric air. Once the tank is filled with this propulsive mass (estimates indicate three orbits should suffice), then the rocket moves to the vicinity of an orbiting beamer and MW/laser energy is beamed to the rectennas/PV on the rocket. This off-board energy powers an MHD accelerator which provides, using the alkaline-doped pressurized atmospheric air as propulsive mass, high thrust at ISP levels of up to 2000 seconds. A rapid acceleration is utilized due to beam diffraction issues, with some future possibility for major reductions in beam diffraction via soliton wave and meta-materials research. Several technologies, including much more efficient/ultra-lightweight rectennas, make this concept interesting. Such an approach could be utilized for orbit raising (LEO to medium Earth orbit (MEO), high Earth orbit (HEO), Geostationary Earth orbit (GEO)) as well as Moon, Mars, and other expeditions. If a beamer is pre-positioned around or possibly on Mars, then a similar approach could be used on the return trip, possibly using regolith as propulsive mass. [ref. 22].

Utilization of advanced nuclear batteries – Advanced nuclear batteries have two major benefits/improvements over earlier versions and reactors: order of some 25 to a factor of a 100 times less weight for the same power, and far more power than previous nuclear batteries. These batteries scale up to megawatts and their light weight enables viable high thrust and high Isp electromagnetic propulsion. They could also be used to power energy beaming as well as thermal or electric propulsion. Additional in-space uses include powering in-space and on-planet habitats, ISRU writ large, on-body transportation and utilization of propulsive mass in general, such as regolith and water, utilizing conductivity enhancement approaches [refs. 6 and 24]. For on-Mars transportation with its variegated typography, flying would be useful in general for beyond walking distances. The advanced nuclear batteries could provide energy for CO_2 breathing for both longer ranges (via heated ingested CO_2), and shorter ranges via a surface effect airborne approach, where the nuclear batteries drive lift fans. Also enabled would be CO_2 breathing for low-cost powered entry, descent, and landing, a possibly major safety, and other metrics advancement.

Utilization of mass drivers – Propulsion is provided by accelerating mass via various means to push on the space vehicle. Variations include high pressure water jets and several variations on the sling, including the Titman slingatron, and the maglifter and maglev. These are usually termed launch assist.

Space propulsion without propulsive mass - Electromagnetic tethers provide thrust working off of in-space magnetic fields, when present, and energy from chemical, solar, beamed, or nuclear. The increasingly severe space debris issues require active removal (especially of the larger piece parts) using a system that is both effective and affordable. E-M tethers, powered by the advanced ultra-low mass and high energy density nuclear batteries, appears to provide a viable lowest cost approach. Solar sails and magnetic sails are also propellantless propulsion. Then there is gravity assist [ref. 1].

Concluding Remarks

Conventional rockets combine propulsive mass and energy and have a "terminal" Isp of some 450 seconds using H_2/O_2. Separating propulsive mass and energy in various ways enables much higher Isp values. Full exploitation of this separation of propulsive mass and energy for space requires high energy densities not yet readily available. The characteristics/capabilities of the new, advanced nuclear batteries would enable higher thrust levels, higher Isp, a greater scope in regard to propulsive mass possibilities, lighter weight, and, due to advantageous scaling, a greater scope of applications beyond propulsion to ISRU and habitats with applicability to the outer solar system.

The benefits of advanced propulsion enabled fast transits to Mars include:
- Reduced costs overall
- Reduced integrated radiation exposure
- Reduced micro g exposure
- Increased reliability due to reduced "duty time"
- Reduced durability concerns/issues
- Less "boil off"
- Less consumables
- Less "psychological" problems
- Improved public engagement due to enhanced "currency"

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