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Frontiers of Space Power and Energy

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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].