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Novel nuclear power sources with application to space propulsion

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Abstract

Nuclear power is still a genuinely new domain with respect to space exploration. The field is still in its infancy, despite of over 60 years of peaceful exploitation of nuclear power on Earth, and many successful applications in space. Nuclear power sources are very compact and may be used for local power generation or as a source for propulsion in advanced thrusters. Fission batteries experience drastic limitations with respect to the energy that might be stored on board a spacecraft, due to criticality issues. Fusion batteries remove this impediment, but fusion energy is in an early stage of technological research. Today, the best propulsion systems are inertial, jet based electric thrusters, providing a owerful source of efficient propulsive energy, but even with the development of these thrusters, travel throughout the solar system within reasonable time scales is unattainable. In the absence of other superior, physics-based propulsion concepts, nuclear-energy-powered jet propulsion may take us to the limits of our solar system, but no further.

Keywords

Nuclear power; Jet propulsion; Electric thrusters; Fusion battery; Fission battery; Isotopic battery, Nano-nuclear; Direct energy conversion; radiation guiding.

INTRODUCTION

This paper presents ideas for novel nuclear energy sources based on new nano-material structures and discusses their applicability to space propulsion. Special emphasis is given to direct energy conversion processes, i.e., the direct conversion of particle kinetic energy into elecric current.

Nuclear energy as we know it today is a technology that requires significant development before it will reach mathurity. In this regard, recently developed micro-nano-hetero-structures are giving a novel perspective to nuclear power, making possible the development of compact, solid state nuclear power systems. Additionally, nano-materials may permit high efficiency light shielding, robust self-repairing of materials structure from radiation damage; or enable the construction of active radiation guiding materials. Radiation guiding materials, conceptually, may be used as antenna coating for directed energy harvesting, for active energy shielding, or as harvesting devices in order to act as space energy concentrators.

These individual devices might be applied jointly, resulting in complex systems with outstanding capabilities and performances. Ultimately, they might provide for comfortable space travel inside the solar system, resulting in relatively acceptable travel times frames, even between future space colonies or space outposts at the edge of the solar system. However, because of propulsion effectiveness issues all of these systems using these advanced concepts are not suitable for human crews in interstellar travel, i.e., one cannot go outside the solar system.

NOVEL NUCLEAR POWER SOURCES

The evolution of nuclear power sources is primarily based on new developments in materials technology. Among these, is the direct conversion of nuclear energy into electric energy, utilizing compact solid-state devices. These direct energy conversion devices rely on nuclear decay, fission, or fusion, and are generi-

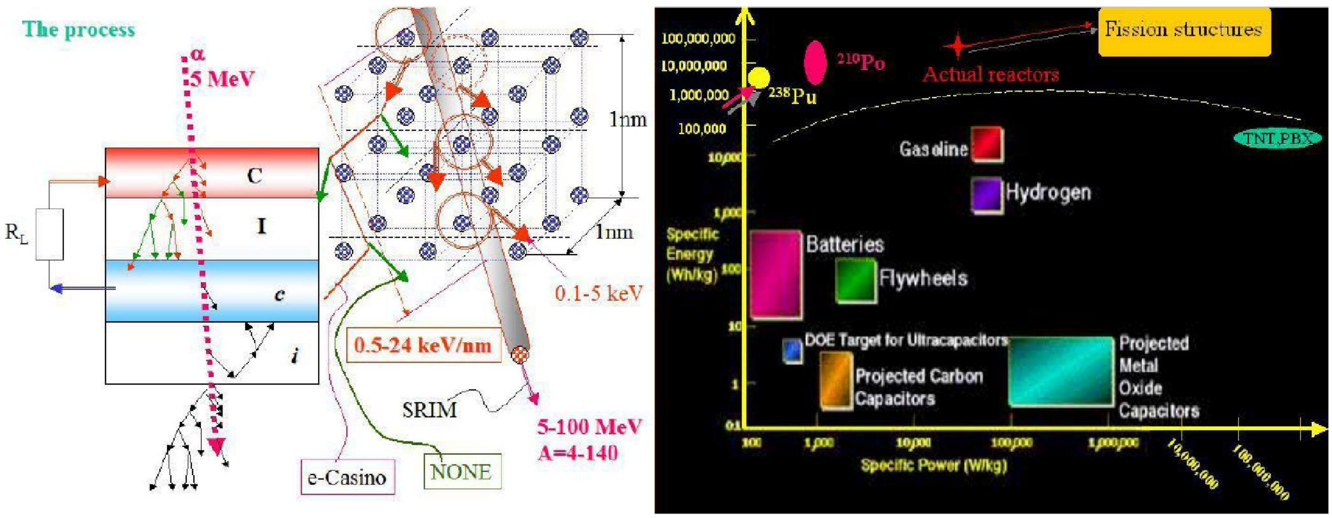


Figure 1 : The physical principle of direct energy conversion is depicted

cally called batteries.

The operation principle of such a solid-state battery is shown in Figure 1, resembling a capacitor that is charged from the kinetic energy of moving particles and is discharged directly as electricity.

The solid-state battery consists of layered materials whose electronic shells are crossed by fast moving nuclear or atomic particles. Such a particle could be a neutral atom or molecule, a fission product, an alpha particle obtained from fusion or nuclear decay, a beta particle (electron, positron), a (gamma) photon, or a neutron. As soon as the particle interacts with the battery material, it gets into a dynamic ionization state[1], shown by the cylindrical gray tube. The particle interacts with the electronic shells by knocking-off electrons, shown by the red arrows that are directed in the direction of motion of the particle. These ejected electrons further interact with other electrons, ejecting them from their orbits, as indicated by the green arrows. The final result is a bulk electron current that has less energy than the initial knock-off electron energy.

If this process takes place inside a repetitive multi-layered capacitor, as shown in Figure 1, left side, it might amplify the polarizing process thus enhancing the conversion of electron kinetic energy into electricity. Such a “super capacitor” can be formed from nano-material layers containing a conductor *C* of high electron density with a thickess of several 10 nm. Intense electron currents will be generated during the sudden deceleration process from the deposited kinetic energy of the moving particle. The knock-on electrons may tunnel up to 100 nm inside the conductor material, followed by a thin layer *I*, of insulator material. Electrons tunnelthrough this layer with little interaction, and are eventually stopped into a layer of conductive material, c, of low electron density. This layer generates only a very small electron shower and is coated by another insulator layer *I*. This quadruple structure is repeated, and the number of these layers is large enough to ultimately bring the particle to rest within this lattice. The plot in the left of Figure 1 shows the novel type of capacitor with its two conductive semi-conductor layers, *C* and *c* that are connected to the (external) load resistor R_L, where layer *c* plot is negatively charged with respect to C. When this kind of novel energy conversion is applied to fission, e.g. a nuclear reactor, it may be possible to eliminate the complete thermo- electric energy conversion system, and thus reduce the size of the power station to the nuclear reactor itself together with only an interface needed for electrical output. The chart (right of Figure 1) shows the performance of various power sources both in terms of power and energy density. It is obvious that nuclear power sources are delivering an energy output three orders of magnitude higher than any other known energy source.

Figure 2 shows the voltage and current distribution inside the super-capacitor. The red layers, possibly made of gold, have a thickness of several tens nanometers and are the high electron conductor nano-layers. It is these layers that are generating the electron shower. These electrons, then, tunnel through the dielectric material and are stopped at the blue layers, which are made of low electron density material, like aluminum. Their thickness has to be large enough to reduce the tunneled electron curent, I_d, (close) to zero, and thus this layer gets negatively charged. Furthermore, the insulator layers need to be thick enough to withstand the breakdown voltage V_{bk} that is higher than the operational voltage V_{op}. The capacitor foils are connected in parallel to the external load resistor R_L (Figure 1, upper right), extracting the current I_{op} at a voltage V_{op}. The power density depends on the power deposition of each particle in the respective layer as well as the number of particles stopped in that layer and, naturally, the efficiency of the energy conversion.

The energy conversion efficiency of these new materials will be larger than the efficieny obtainable from any of the current nuclear power plants, also including thermo-electric convertors (TEC) with a conversion efficiency lower than 10%.

The direct energy conversion structure has several constructive variations, as shown in Figure 3. It can be built from planar depositions (Figure 2), but there is a disadvantage in that most of the heterogeneous structures deposited in such nano-layers possess the tendency to separate and precipitate, forming nano-beads at higher temperatures. This kind of structure modification limits the operation temperature of planar nanostructures, but there exist other structures (see below) were conceived that might successfully operate at higher temperatures.

Care must be taken when the dimension of the structure is decreased down to the nanometer range (Figure 3 upper-left), because quantum effects start to dominate and the local material properties strongly differ from those of the bulk, giving rise to spherical charge reflection on a grapheme foil creating quasiparticles that are collective excitation within a material that behaves like a fundamental particle, i.e. a plasmon or a dropleton which comprises a small number of electrons and holes that are bound together.

The upper-right of Figure 3 depicts the dimensions and properties of super-cpacitor material in order to be able to sustain the indicated power density (compare measurements in Figure 3 upper right). For example, consider a planar-layered structure of a volume of 1 mm^3, where edge effects are neglected. The structure is supposed to be made of silica and gold-aluminum (bi-layer), and thus should sustain a voltage of more than 10 kV. The admissible current is 0.5 A or higher. That is, a total power of 5 kW/mm^3 might be achieved, which is about *three orders of magnitude higher* than the largest power density achievable in nuclear reactors (maximum of about 1 kW/cm^3).

Though metamaterials have the capacity to store and carry a huge electric power density, as shown in Figure 3 upper right, in practice the generated power density is still drastically limited by the energy conversion efficiency. Any energy not converted into electricity being removed from the structure becomes waste heat, generating the corresponding heat flow. For example, by assuming a conversion efficiency of 90% and a resulting heat flow that is equivalent to a power density of 100 W/cm^{3,} the maximum power density is limited to 1 kW/ cm^3.

The lower-left picture of Figure 3 shows a bi-material nano-beaded structure embedded into an amorphous

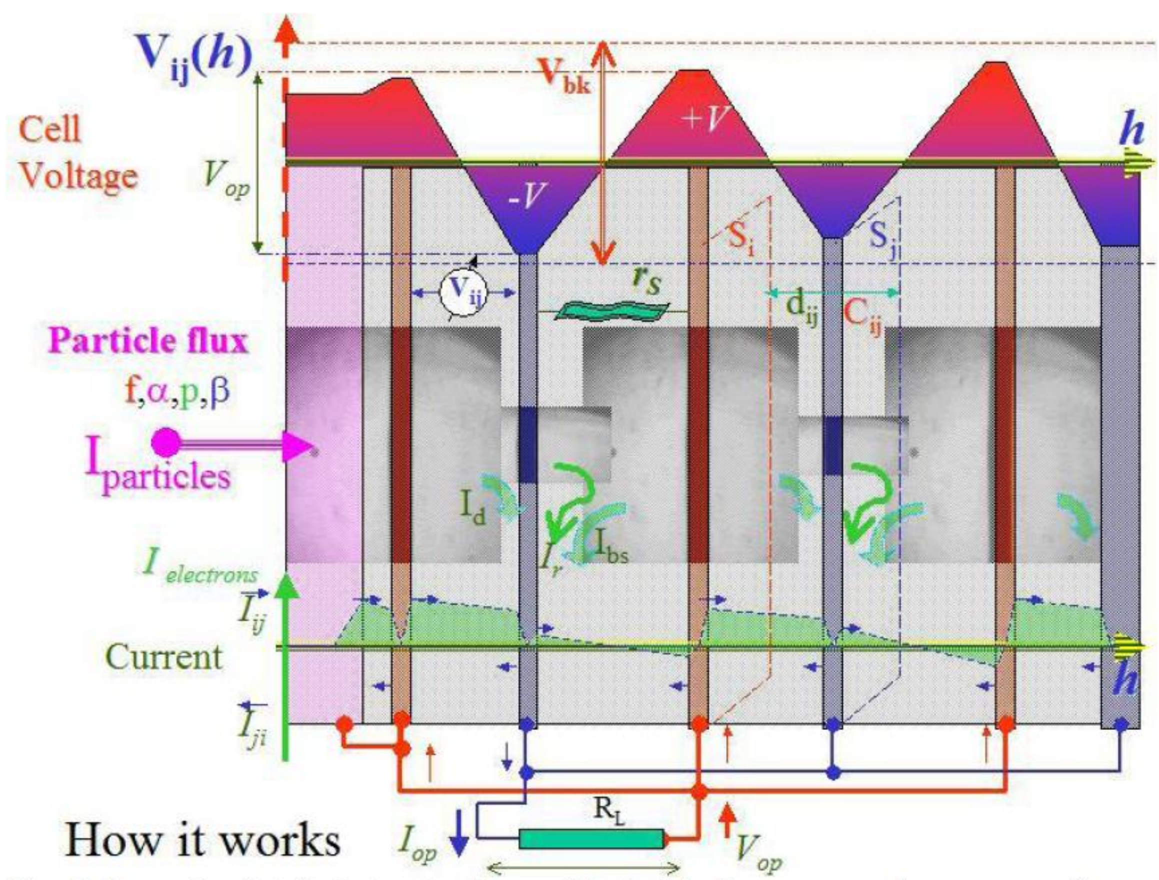


Figure 2 : Shows the detailed structural assembly inside the prpoposed super-capacitor

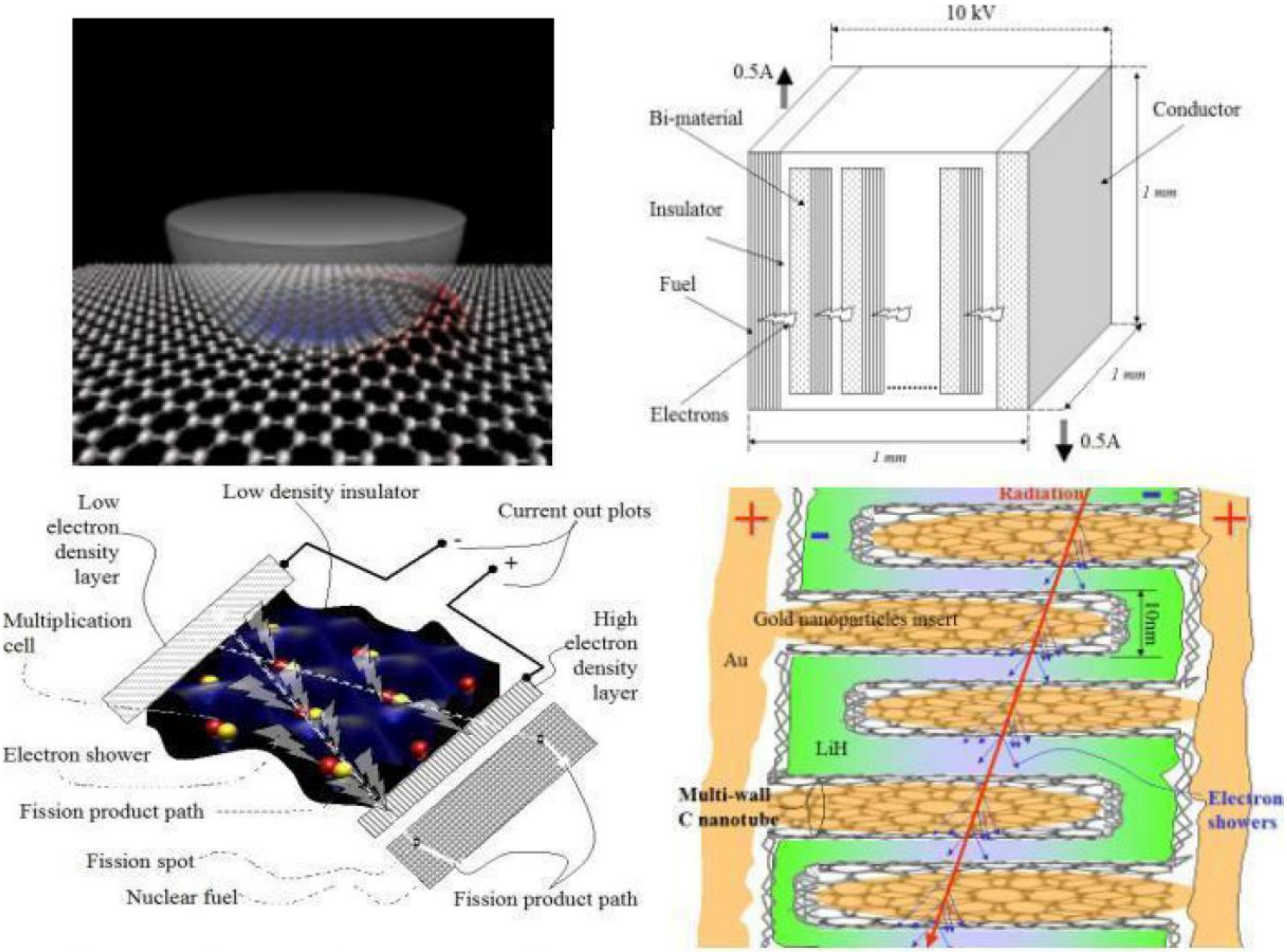


Figure 3 : Various fabrication techniques for nano-hetero structures for direct nuclear energy conversion

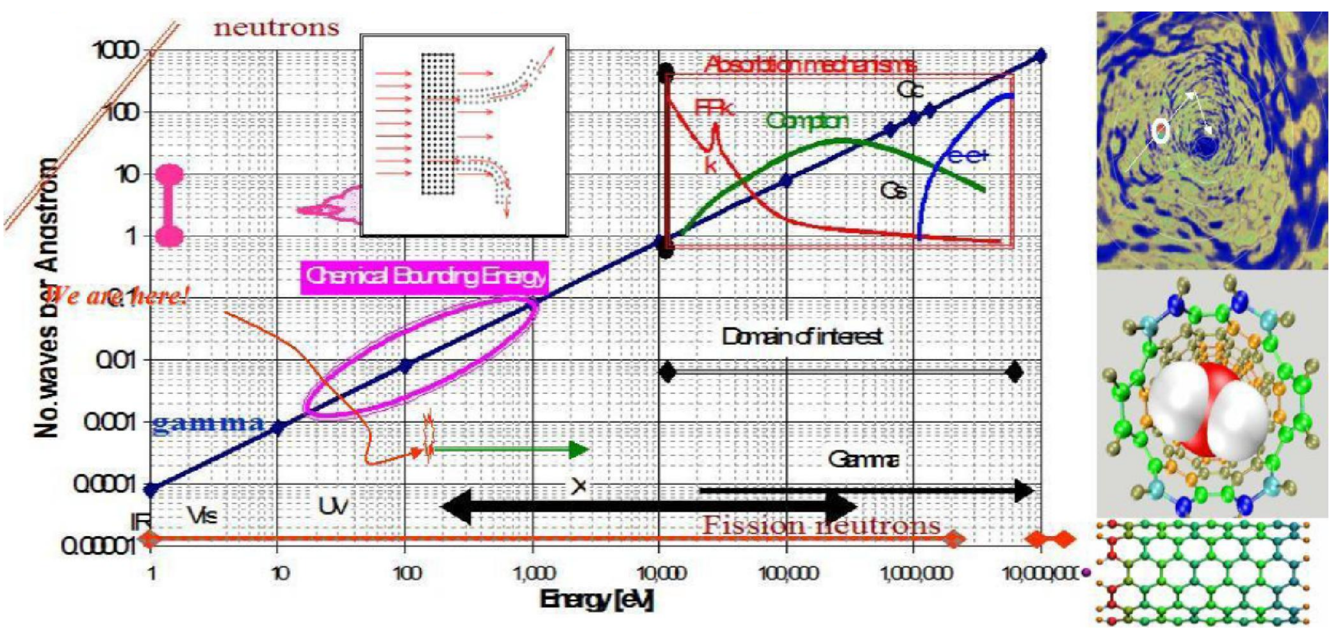


Figure 4 : The principle of radiation channeling or guiding radiative energy in solid structures

silica insulator, where the beads are connected in series by knock-on electron discharge induced by the moving particle, representing another variant of metamaterial structure.

This structure presents the advantage of operating at higher temperatures of up to 1,000 K, where the power density of the heat flow may reach 0.5 kW/cm^3, offering the possibility of higher electric power density,

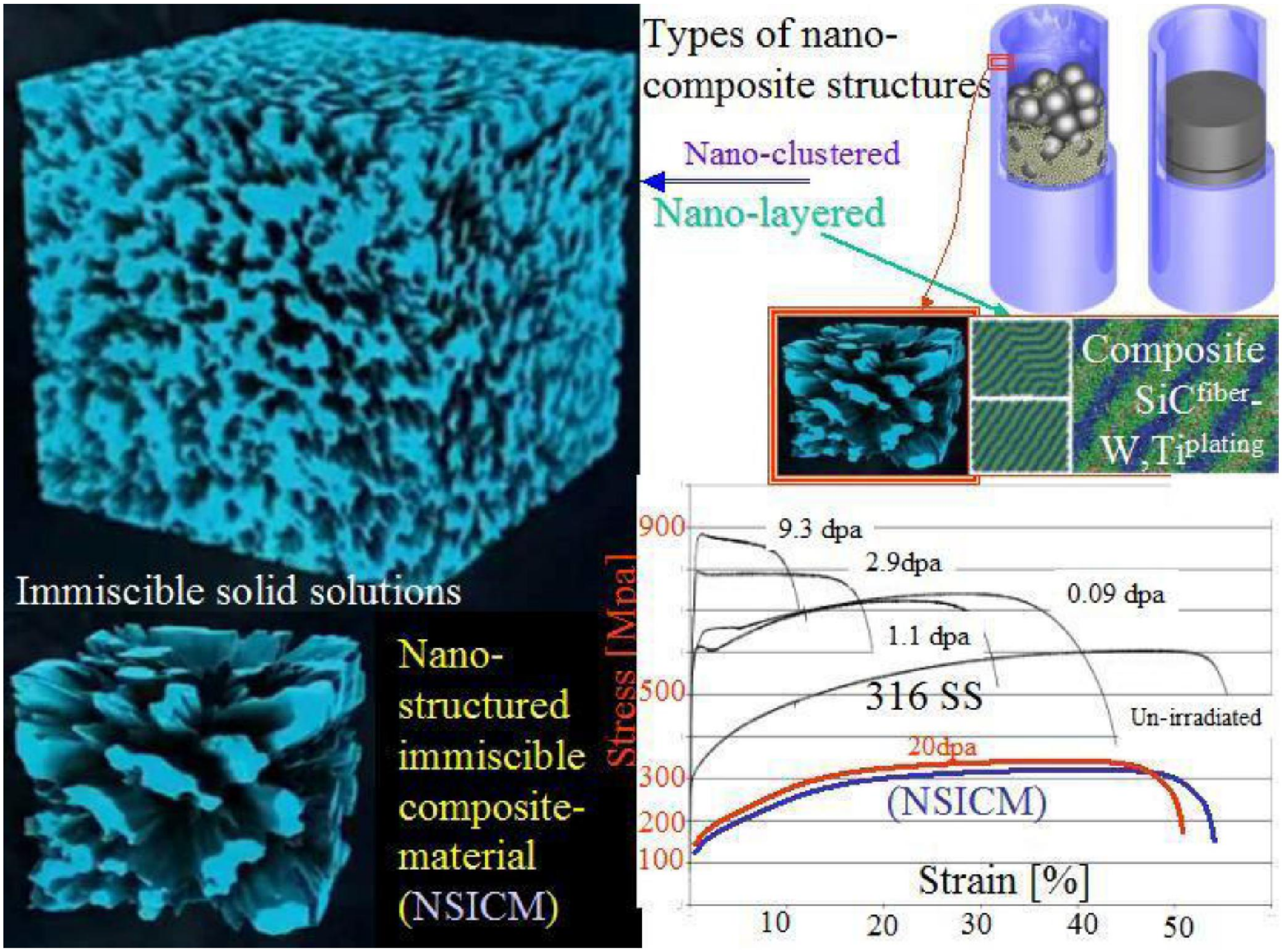


Figure 5 : Radiation robust materials

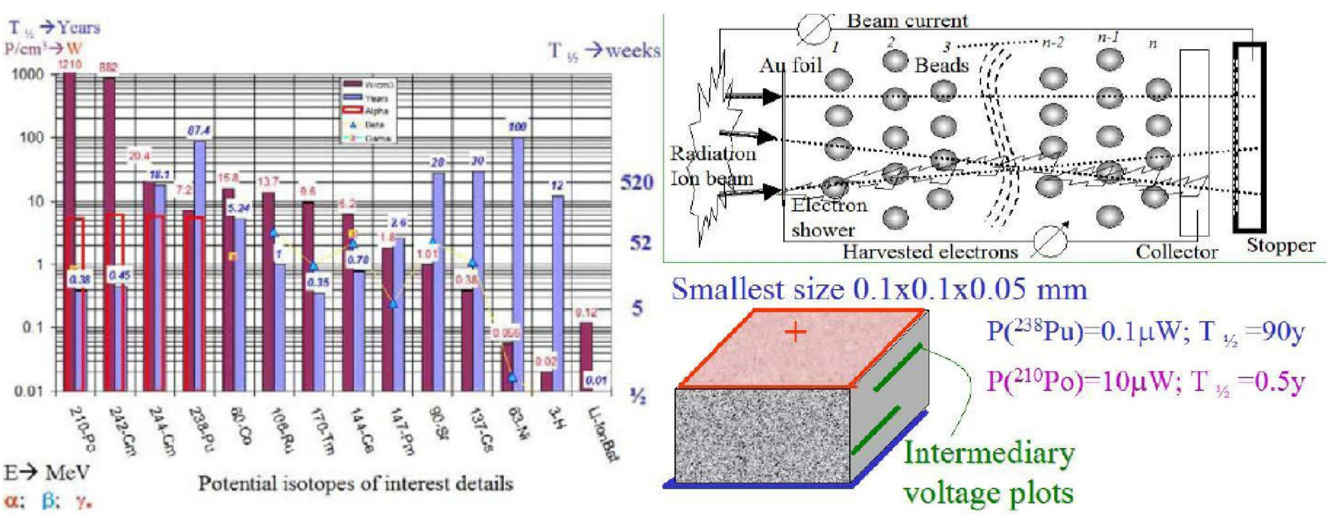


Figure 6 : Isotopic battery power sources structure and specific energy dependence of the employed radioisotope

along with a supplementary thermo-mechano-electric conversion that may add up to 150W/ cm^3, further improving the overall efficiency.

The lower right of Figure 3 depicts a loaded-multi-wall nano-tube construction that operates for a large solid angle (moving particle geometry) being another constructive variant of direct energy conversion structure. Though operating at lower temperature, this structure may offer very good energy efficiency.

Radiation guiding devices

Since the 1970s it has been observed that radiation may be channeled inside crystal structures[2]. More recently nano-structures are used[3] to channel radiation, and to make devices that control direction of neutrons and X rays.

Figure 4 (upper-left) shows the principle of radiation guiding in nano-structures. A portion of the incoming particle flowis trapped inside the nano-structure that may be a nano-tube, nano-wire, or patterned structure. The trapped particles then interact with electric and magnetic fields inside the structure, and subsequently are smoothly diverted at grazing angle, thus being driven forward along the tube.

The figure in the middle (upper part) presents a view along the guiding tube, seen from behind the neutron, along the displacement direction. The structures in blue and yellow depict magnetic fields with different polarities produced by the nano-structures. The interaction of the neutron momentum with the structure material is collective-repetitive that is, many atoms from the guiding tube structure interact only wealy with the moving particle, diverting and turning it, and, only occasionally, scatter it into the opposite direction without significantly modifying its energy, i.e., the scattering process is elastic. This process resembles the focusing/defocusing that occurs in FODO (FOcusing/ DefOcusing) structures, employed in storage rings of particle accelerator systems.

The upper-right figure zooms inside the channeling tube, showing the atomic bonds, illuminated by the touch of the (dipole) magnetic moment of the moving particle.

The chart at the bottom shows the associated wave length for photons (blue line) and neutrons (red double line) plotted versus energy. The energy that is guided through the tube is shown by the pink ellipsoid for X rays, whereas the red segment shows the energy for neutrons. In addition, the domain in which X and gamma rays have to operate for the next generation of guiding tubes is also shown.

There exist many applications for this type of device, for instance, in radiation shielding, or concentrators (with or without imaging capabilities). Nuclear reactor shielding may be made of absorption blankets. Active control of criticality can be achieved by using blankets made of nano-guides to which a NEMS (Nano-Electro-Mechanical System) device is attached, in order to provide electronic commands in selecting the particle route, i.e., back toward the reactor core for increasing reactivity. Alernatively, particles can be made to move toward an absorber to increase transmutation as well as to reduce power. The response time of these NEMS is in the micro-second range, producing an outstanding degree of control.

RADIATION ROBUST MATERIALS

Structural materials utilized in nuclear reactors deliver very good mechanical performance by having a small neutron absorption cross section, but are sensitive to radiation damage that makes them swallow and embritter.

New types of sintered materials have been developed to obtain material properties that remain constant for large radiation doses. These materials must have an optimized microstructure with regard to the type of radiation damage and the specific application. There exist immiscible solid solutions, as shown in Figure 5 at bottom left, that offer good mechanical properties that remain almost independent of the radiation level. To demonstrate this behavior, the mechanical behavior of stainless steel SS316 is shown and compared to nano-structured composite material in the diagram at the lower right of Figure 5. The upper right of Figure 5 shows several other types of composite nano-materials that are supposed to also possess good robustness with respect to radiation damage.

ISOTOPIC BATTERY

An isotopic battery directly converts the kinetic enegy of nuclear decay products into electric energy which is then stored in a nano-hetero-structure. The battery is powered by a micro-layer of radioactive material comprising (mainly) alpha or beta emitters.

Figure 6 (upper right) shows the schematic diagram of an isotopic battery. The battery is made of a nano-beaded structure embedded in amorphous silica, plated on one side with gold and on the other side with a layer of aluminum (or other materials of similar functionality). If alpha decay is used as the energy source, the layer thickness should be about 20 microns. The alpha-emitter itself has a thickness of a few microns incorporating a gold substrate acting as electron shower generator.

A battery can be made, upper right figure, from multiple layers containing intermediary voltage plots, thus enabling customized voltages for a variety of applications. The bar chart below plots power densities from alpha radiation (red bars on the left axis) for different isotopes together with lifetime (blue bars). The preferred power sources are based on alpha and beta decay and preferablly do not generate gamma or X rays, as is, however, the case for ^{238}Pu or ^{90}Sr. The lowest footprint of such a battery, or, in other words the smallest area (for normal conversion efficiency) is about 100 x 100 microns and its thickness is some 50 microns. The radioisotope is contained between two conversion-foils, each about 20 microns thick. This geometry matches the power (left side) obtainable from ^{238}Pu and ^{210}Po, producing basically the same energy output. Such a configuration is equivalent to more than 50,000 chemical batteries, having a weight, in the range of 1 to 3 chemical batteries weight, depending on the structure used inside.

In the future this type of battery might be a candidate to replace the actual thermo-electric converter elements, operating by converting heat into electricity. These devices are also known as RTG (Rradioisotope Thermoelectric Generator), delivering a conversion efficiency less than 10%. Moreover, even the novel power sources based on the Stirling or Brayton engine-generator can only reach conversion rates up to 30%, but due to the presence of moving parts, have lower mechancal reliability. A special feature of isotopic batteries is that their power output cannot be adjusted at will, since the energy is generated from natural radioactive material.

FISSION BATTERY

This is a new device that uses the same direct nuclear energy conversion for electricity generation. The fission products deliver about 170 MeV per fission act, equivalent to 25 pJ. The fission battery has the advantage of producing 20 times more energy (per moving particle) than a source powered by alpha decay.

Figure 7 shows the functional diagram of a solid-state fission battery. This device, which is similar to an isotopic battery, has ^{235}U or ^{239}Pu based fuels embedded between the conversion structures. The necessary condition for such a structure to operate is to meet the criticality conditions and to have an adjustable system for the neutron flux. For any configuration, in order to meet the criticality conditions, structures with a diameter larger than 1 m are required, where all of them need to be comprised of nano-structures, which represents a substantial challenge for the manufacturer.

FUSION BATTERY

Recent advances in physics make it possible to use long-range nuclear reactions, triggered by low energy quantum changes, in order to induce high-energy quantum reactions. This effect was discovered experimentally in the 1920s, and since that period more than several hundred successful systems were fabricated. To understand the phenomena presented in Figure 8, a more thorough understanding of quantum and higher-dimensional physics is necessary to properly account for entanglement, quantum – nuclear active environments, and higher multi-dimensional spaces.

It was experimentally proved[4] that fusion reactions do occur in quantum-nuclear active environments under special conditions. The upper-left side of Figure 8 shows a Pd–D lattice that is self-excited by random temperature effects. Alternatively, the lattice might be excited using electro-magnetic fields applying resonant frequencies in the THz range. In this environment, a He nucleus spontaneously emerges from the fusion of two deuterium nuclei, mediated by the palladium lattice. The process of fusing two deute-

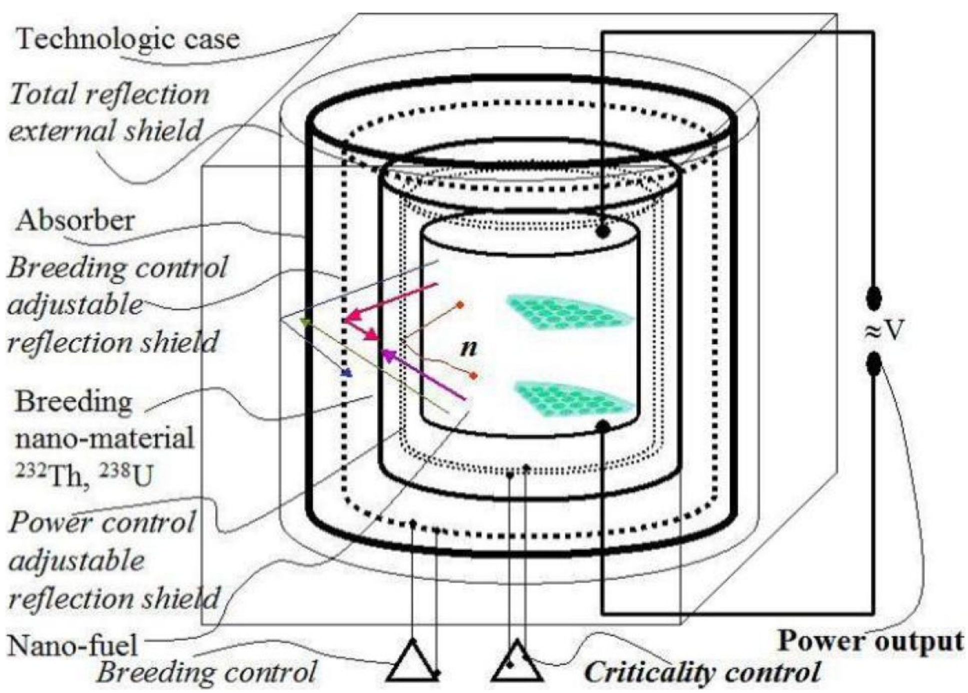


Figure 7 : Sketch of solid-state fission battery

rium nuclei into a single helium nucleus, as shown by the picture underneath, releases about 22.4 MeV per fusion reaction, where 22 MeV is due to the kinetic energy of the ejected helium nucleus, and about 300 keV is attributed to the recoil kinetic energy of the palladium nucleus. These nuclei produce over 10,000 dpa (displacements per atom) in the region, thus destroying the quantum-nuclear resonance of their environment, as indicated by the two stars in the upper-left picture. If this structure is embedded into a direct energy conversion structure, as shown before, the palladium and helium energy may be harvested and delivered as electricity, as depicted by the lower-left image.
A very simplistic explanation is expressed graphically in the upper right picture[5]. Self-excited nuclei have a special state of matter that develops along some fibers of space,[6] outside the force-field of the electric shell (a nucleus has an apparent radius of a few fm, e.g. ^{12}C has a radius of about 2.8 fm), and extends far beyond. As demonstrated by special entanglement communication experiments, a state of quantum correlation may be maintained for hundreds of kilometers. It is also known that entanglement is continuously created and destroyed and that the kinematic equilibrium depends on amost all properties of the environment in which it takes place. Communication experiments also cope with teleportation of quantum states and non-locality. In our case, if these fibers of space with special properties, as entanglement or teleportation emitted by the palladium and deuterium nuclei, should be touching each other, as happens at points C1 and C2, as shown in Figure 8, those nuclei are supposed to be in a special state of *communion*, similar to the one obtained in head-on collisions of accelerated particles breaking through the Coulomb barrier. In this case, they simply ignore the electric field by communicating and interchanging their quantum states, taking a new stand in accordance with the requirements of the quantum-nuclear active environment. As soon as the stand has been taken, the new manifestation takes effect and new nuclear particles and states appear, in the form of fusion, transmutation, and even fission[7].
In our case, we are interested in generating those quantum environments leading to fusion, because the kinetic energy of the resulting fusion products will be harvested in the nano-hetero structure customized for this process. Such a device is shown in Figure 9, and it is called the *fusion battery*[8].
The fusion battery is made of a quantum-nuclear active microstructure, which is surrounded by direct nuclear energy conversion (DNECE) structures that harvest the kinetic energy and deliver it as electricity.
A fusion battery contains a deuterium tank from which the gas is loaded in a controlled manner into

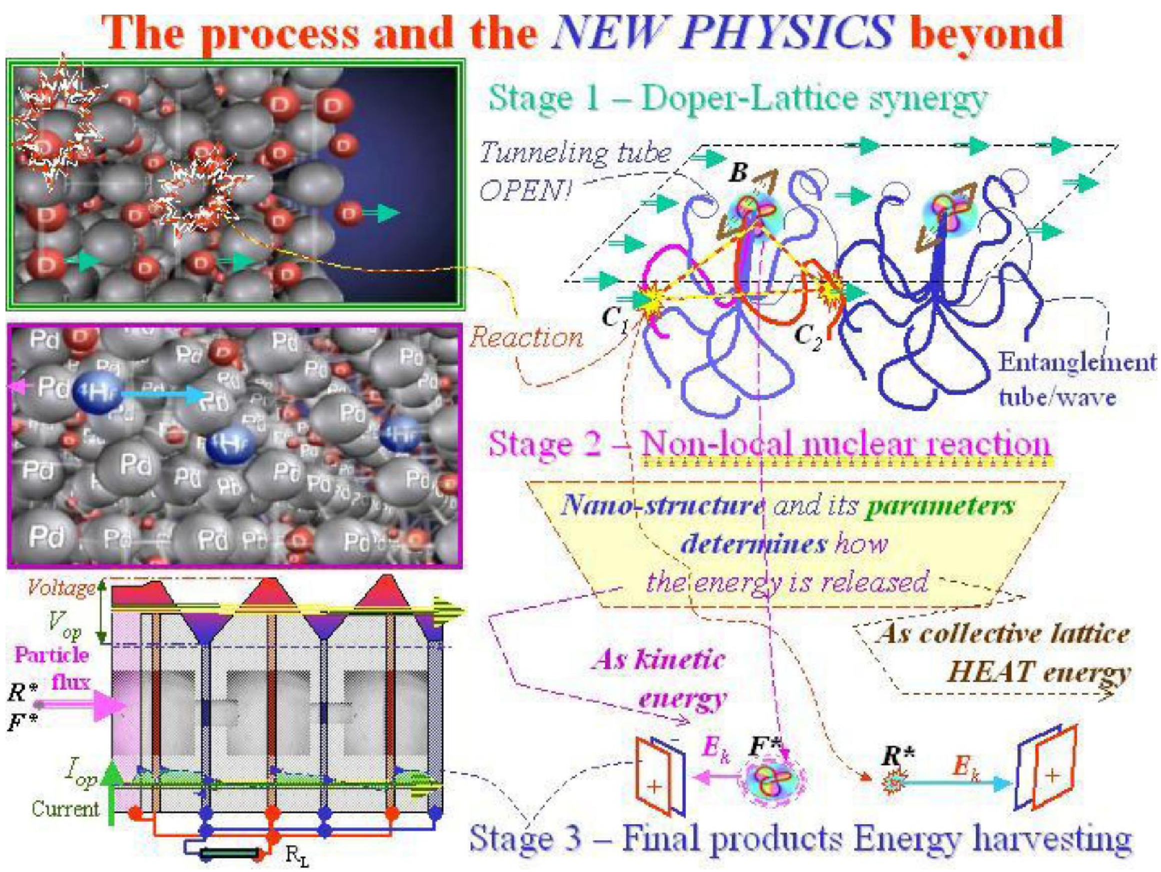


Figure 8 : Physical principles of long-range nuclear fusion and transmutation

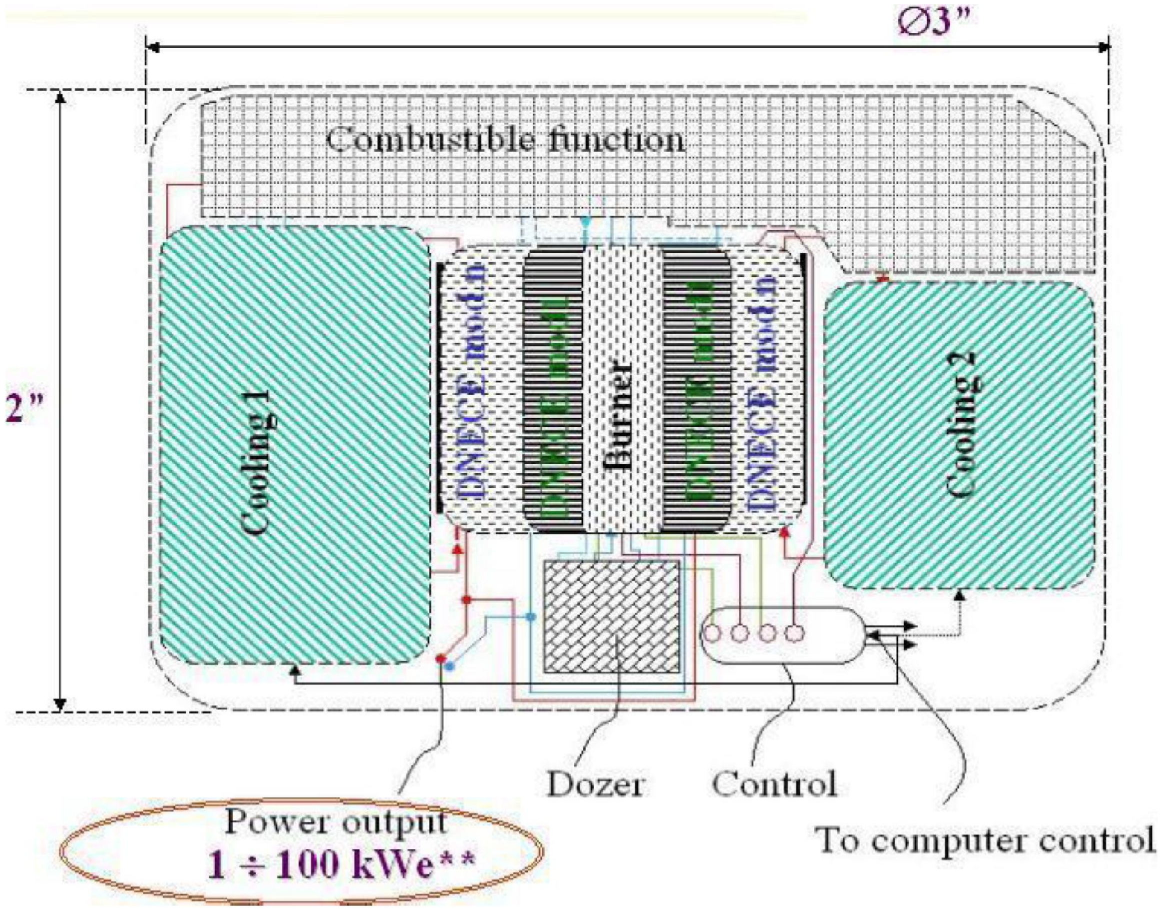


Figure 9 : Modular diagram of the proposed fusion battery for stage 4: building the functional device

the structure, and together with the excitation control, the reaction rate and hence the power output is controlled. The system is surrounded by cooling equipment based on internal helium cooling for the active structure that is taking out the heat to the external heat exchanger, keeping the temperature within operating limits. For high temperature systems a thermo-mechano-electric system might be included in the cooling system, producing some extra energy. The structure is compact and, by computer control, delivery of energy is regulated.

Annihilation battery

Previously discussed sources of energy convert the binding energy of a nucleus, released after a nuclear state change, into electricity.These nuclear sources are about six orders of magnitude more compact than corresponding chemical energy process that convert the binding energy of their electronic shells. The next stage of energy conversion is related to the existence of matter as a condensed state of energy and its symmetrical partner (with respect to vacuum energy), called anti-matter. By burning ^{235}U, one obtains 1 GWDay/kg, about 3 GWDay/kg for deuterium, and about 1,200 GWDay/kg for annihilating hydrogen.

Since the energy density obtained from matter-antimatter annililation is about three orders of magnitude higher than from fission processes, harvesting annihilation energy becomes an extremely difficult task comparable to the storage of antimatter. For instance, the reaction of only 1 gram of matter-antimatter releases the energy of about 0.1 MtTNT. At present, the energy obtained by annihilation of all the antimatter yearly produced at Fermi National Laboratory in US is a little bit over 0.05 kWh.

Other applications

Figure 10 briefly discusses several different, but very important applications of nano-engineered structures. Shown are: a body (or volume) radiation shielding (left figure); same as the for protecting the electronics against detrimental radiation events is depicted. The right presents the (already discussed) fission battery, using advanced control based NEMS (Nano-Electro-Mechanical System), together with radiation guides and DNECE (Direct Nuclear Energy Conversion in Electricity) structures.

RESULTS AND DISCUSSION

Although the above-presented types of nuclear devices

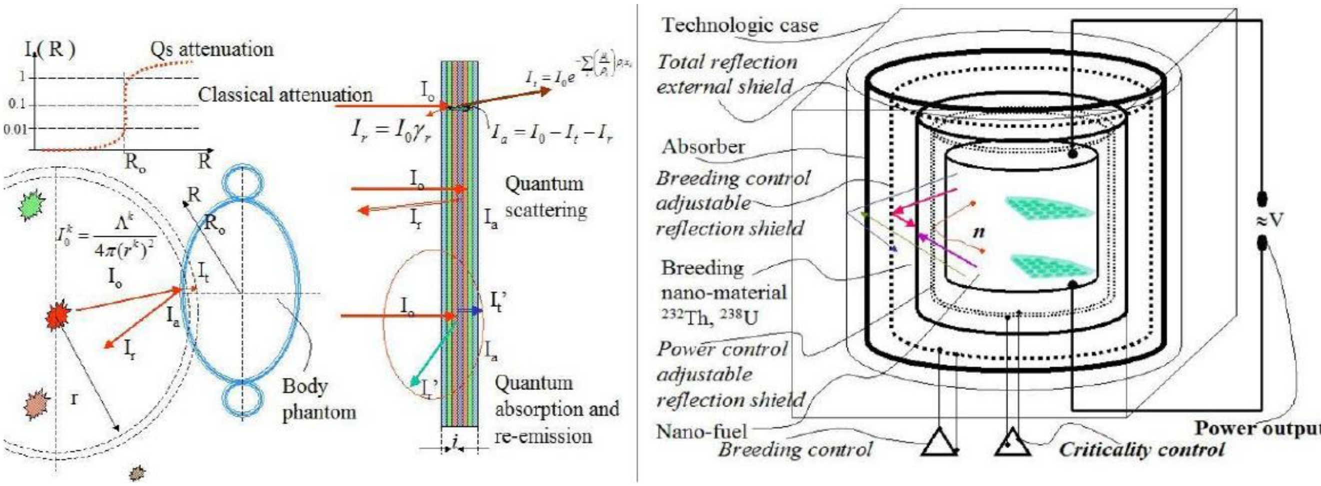


Figure 10 : Applications of advanced nano-engineered nuclear materials

Figure 11 : Near Earth strategic applications of nuclear power systems

have many applications in terrestrial power systems, these devics are most outstanding in extreme environments (including underwater applications). These new compact, silent, high power sources may also allow more advanced propulsion methods, providing long operation hours, and thus a seamless presence in all strategic locations in space should be achievable.

Directed energy devices in low earth orbits

Right now there are numerous space missions under design that require powerful, portable solid-state energy sources that could make use of the above-cited fission or fusion batteries or an isotopic battery that delivers continuous power. In the absence of such power supplies, designs have to be based on solar energy that requires extremely large solar panels. Apart from their size, these huge structures are easy to detect and annihilate and therefore are less useful for military space applications.

In Figure 11 several space projects are presented, all of them requiring compact high power sources in outer-space. The upper left figure presents altitude versus range for various weapon systems, currently used in local conflicts. Also presented is the capability of airborne or space systems equipped with directed energy devices to disable their use, inflicting minimal damage to the enemy but enforcing peace talks or negotiations.

Low and high terrestrial orbit vehicles require megawatt level power on board, power that only a nuclear source can deliver in a compact manner. The center picture shows a scenario for neutralizing an intercontinental missile using kinematics impactors, launched as missiles by a BMD (Ballistic Missle Defense) system that is located at the Pacific and west coast of the U.S. and Canada. These missiles have a certain failure probability, or may cause an unintended deflection of the flight direction of the incoming (target) missile, and thus require at least two launches to secure a 90% hit probability. The window of opportunity for missile launching is less than 5 minutes, in order to have interception at mid range. Instead, by using directed-energy devices from outer-space platforms poses practically no constraint on the annihilation shot, i.e., a total flight time of about 20 minutes is available for defense.

In the center of Figure 11 a directed-energy device is presented, carrying a high power laser, ion beam accelerator, or microwave pulsed power device as part of an active denial system. The power level requirement is over 10 MW for few minutes action, which would be very difficult to achieve using solar panels.

The top-right of Figure 11 shows dummy satellites (in orbit around the Earth) that, by using a direct energy conversion antenna, are remotely receiving substantial amounts of energy through a neutral beam scooted from a directed energy platform, for activating the satellite, enabling a specific mission, or switching it back in stand-by mode.

Another very effective weapon in space is the molted metal or plasma jet directed toward the target. This type of weapon overlaps with the advanced jet propulsion system, which uses a more dispersed jet, but almost employs the same physical principles applied in reverse.

Another most valuable and challenging developments of the future is the steering of asteroids. Not only under the aspect of deflecting asteroid trajectories away from the Earth orbit. As an alternative, the trajectory of an asteroid that is bound to collide with the Earth might be modified by changing the course of other asteroids in order to deflect the otherwise impacting asteroid[9]. Calculations show that to vaporize a large asteroid with a diameter of about 500 m, the continuous use of an IR (infrared) laser beam of 50 MW power for about 1 year[10] is required, delivering an energy output of about 2 PJ (PetaJoule), which corresponds to a power source of about 200 MW. Only nuclear power can deliver this amount of energy, which is equivalent to a solar array of 1 km^2, which poses a real (but impossible to meet) challenge for any space station. In this process 150 MW turn into low grade heat at temperatures of about 400 K. Getting rid of such a large amount of waste heat for the period of 1 year, poses a major technical challenge, and requires a heat sink of about 1 km^2 surface area in combination with a heat exchange agent (fluid). In space, the efficiency of a directed energy device is critical and efficiencies over 90% are desired. An alternative to lasers would be a linear accelerator, which exhibits high efficiency, but the capacitance of a 500-m asteroid is less than 1 mF, and in less than 1 s its electric charge is deflecting the beam. A single charged beam will become divergent due to space charge built-up. A possible solution could be to use blended dual beams at energies assuring optimal penetration depth. The temperature of the target volume would be brought up to about 5,000 K and a mass jet would be locally created, to both provide thrust and modify the asteroid trajectory, (hopefully) away from a collision course to a near miss.

Nuclear powered propulsion

Since the 1950s a new type of propulsion involving the use of nuclear power[11, 13] has been extensively researched, but, in spite of the magnitude and excellence of this research work[14], nuclear propulsion still does not match the performance of actual chemical propulsion sytems[15].

From the exceptional research and the inventions presented[15], only a few examples will be mentioned. The technologies described here are all in the conceptual phase, but have some collateral experimental and computer simulation successes.

Jet propulsion today is the most advanced and reliable propulsion scheme we know, but it relies on chemical fuel and delivers maximal exhaust speeds of some 4,500 m/s because of the limited chemical reaction energy (10 eV per molecule or atom). Chemical propulsion requires bulky fuel tanks. Chemical propulsion is also dangerous, because the combination of two highly reactant materials like liquid hydrogen (LH) and liquid oxygen (LO) requires a very high level of technologic performance (e.g. maintenance intensive cyrogenic fuel pumps). Other fuels exhibit a high level of toxicity, increasing the technological challenge even further.

To provide the reader with a picture of the compactness of nuclear energy compared to chemical fuel Figure 12, upper left, shows the energy equivalent of 2 GWDay in a jar that contains pure ^{235}U or ^{239}Pu. The upper-right side shows a chart depicting the difference between energy and impulse (thrust). In order to increase thrust, mass must be ejected at high speed, but the (nonrelativistic) energy of the ejected mass is growing faster than the thrust, since it is proportional to the square of the exhaust velocity. Therefore, ejecting additional mass becomes more efficient only up to a limit, after which the jet speed has to be increased. This leads to the conclusion that there is an optimal mass-speed ratio.

The picture on the lower-right of Figure 12 shows that, based on the rocket equation, the maximum velocity of the rocket is limited by the exhaust velocity v of the fuel, and thus there is a need to increase the exhaust velocity in order to obtain the optimal performance.

Under practical circumstances there is a limited amount of energy on board, symbolically represented by the uranium in the jar (upper right of Figure 12). The exhaust speed (and also the mass flow rate) are adjusted in order to maximize performance (i.e., minimizing fuel consumption) for a given flight trajectory. This translates into a complex, time dependent optimization procedure.

There exist limitations for the usage of nuclear power in space that are not directly obvious. The relationship between the energy stored in the actinide fuel and its criticality is easy to understand in terrestrial nuclear power, but the problem of how to maximize the stored plutonium and, at the same time, minimize the total mass of the storage so far was not of interest, but will become important with regard to space applications. The residual heat generated by nuclear fuel is a major problem in space applications. Figure 13 shows a chart depicting the use of nuclear power for terrestrial applications. It is well known that the application of nuclear power on Earth has fewer constraints than in space applications, and most of the technical solutions used on Earth will prove impractical in space. Very important limitations with respect to the total mass of fissile fuel that can be packed into an operational nuclear structure are revealed in reference[16]. The upper part of Figure 13 pictures various nuclear power structures that represent an optimum to reach both criticality and to allow a continuous mode of operation. It is clear that by replacing materials of low neutron absorption cross section by those of high neutron affinity, one may reduce the mass of the structure and maintain its sub-criticality for a ratio of ^{235}U in ^{238}U as encountered in depleted uranium. The jar, as pictured, is meant to contain natural uranium that is, this mixture includes only 0.7% ^{235}U. By contrast, if highly enriched uranium were placed in such a geometry, the hazard of a criticality accident would rise substantially. The figure to the right of the jar depicts the waste fuel storage, followed by the CANDU reactor picture, which is operated by natural uranium and heavy water. Next, a light water reactor (PWR) is presented. The right-most picture shows the principle of operation of nuclear detonation devices. Underneath these figures, a table of critical masses for various heavy metals actinides used in nuclear power is given, being meant to give a complete image of the complexity of this domain as well as the challenge of getting it ready for space power applications. Figure 13 shows (in blue, data points are marked by squares) a plot of the total mass of a nuclear structure (right ordinate, logarithmic scale) versus enrichment level. The left ordinate gives the total mass of the fissile material (in red, linear scale) as a function of enrichment level marked by blue dots with error bars.

The straight dashed lines that are a fit of the total nuclear mass data, show the domains of the heavy water (D_2O) moderator, light water moderator (H_2O), and for weapons fuel (W). The dashed red curve, repre-

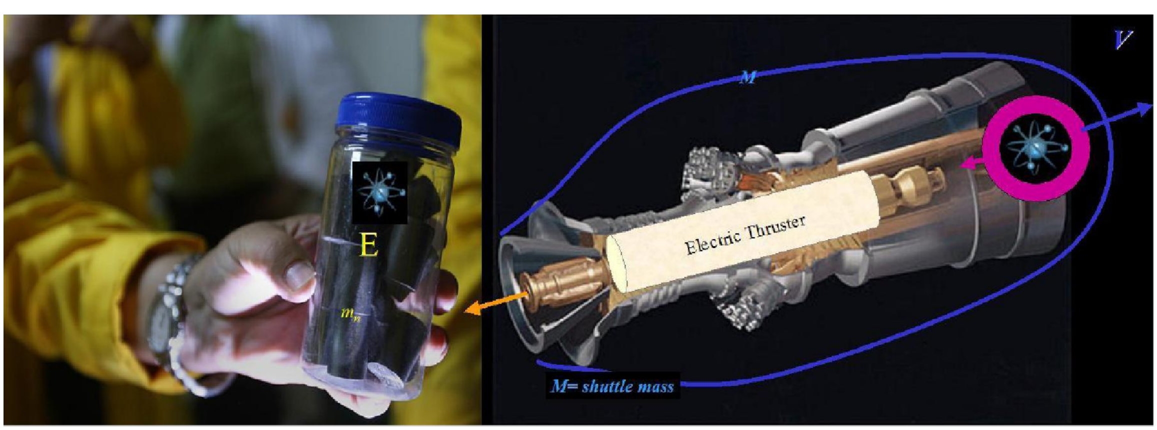
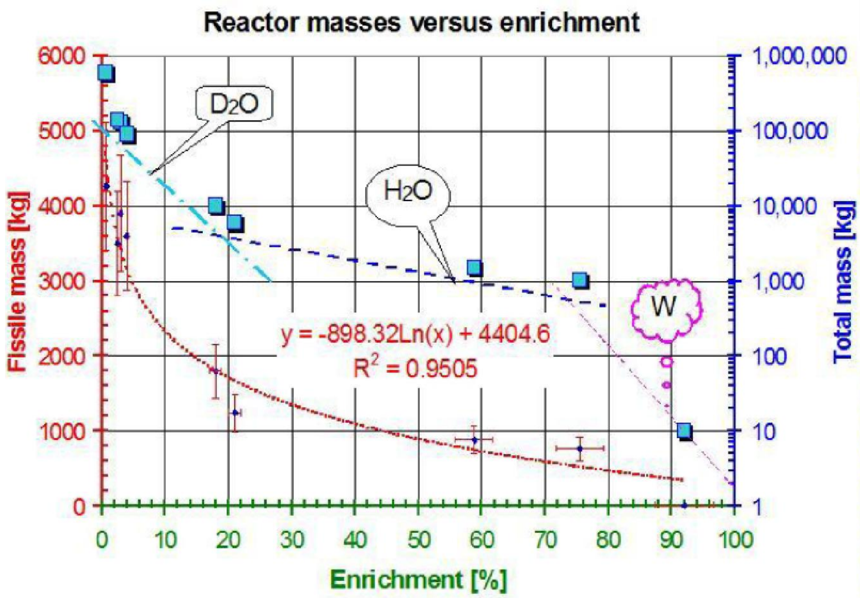


Figure 12 : Nuclear propulsion



Nuclide	Critical Mass (kg)	Diameter (cm)
uranium-233	15	11
uranium-235	52	17
neptunium-236	7	8.7
neptunium-237	60	18
plutonium-238	9.04–10.07	9.5-9.9
plutonium-239	10	9.9
plutonium-240	40	15
plutonium-241	12	10.5
plutonium-242	75–100	19-21
americium-241	55–77	20-23
americium-242	9–14	13-Nov
americium-243	180–280	30-35
curium-243	7.34–10	11-Oct
curium-244	(13.5)–30	(12.4)–16
curium-245	9.41–12.3	12-Nov
curium-246	39–70.1	18-21
curium-247	6.94–7.06	9.9
californium-249	6	9
californium-251	5	8.5
californium-252	2.73	6.9

Figure 13 : Total fissile fuel mass limited due to criticality issues on board the space shuttle

senting a logarithmic fit, approximates the fissile mass needed. In other words, an upper practical limit of the energy stored would be under 5 GWYear, which is equal to the mass of a 1 GW_e PWR reactor to be transported into space, containing, however, highly enriched uranium (HEU). Such a space vehicle will be difficult to launch into a LEO due to its huge mass and might have no practical use.

On the other hand, observing terrestrial applications, the higher the operation temperature of nuclear power sources, the lower is their total power, as can be seen from the chart in Figure 14 (lower right). An exponential fit line has been obtained for operation temperatures between 500 K and 1,000 K.

Similar to Moore's law used in semiconductor industry, there is no law of physics to enforce the variation of the power with operation temperature. This effect is the result of human perception on the safety of nuclear power operation that sees in high temperature material a higher hazard, due to proximity to meltng and evaporation points. Because of the Maxwellian speed distribution (upper-left of Figure 14), for nuclear jet propulsion to become competitive to chemical propulsion, higher operation temperatures are necessary in order to obtain higher molecular velocities in the exhaust jet. The upper-right gives the numerical data for hydrogen, the most common fuel for space propulsion. The table lists the parameters for several chemical rocket fuel combinations. It can be seen that the required operating temperature for a thermal nuclear device has to be higher than 2,000 K to render it superior over chemical propulsion.

As shown in the lower chart of Figure 14, the expected power consumption of such a device is lower than 10 MW. This value is also confirmed by the previous nuclear programs from the 1950-1970s, where test power was below 1 MW. With this power available, at a working temperature well over 2,000 K, the mass flow is small and so is the available thrust, but the duration of the generated Isp (specific impulse [1/s]) might be much larger than for chemical propulsion (several minutes only), resulting in an operation mode basically defined as continuous operation.

The novel structures relying on nano-technologies deliver electric power that can be optimally used in high efficiency electric thrusters, delivering the required speed and flow rate. In these systems the velocity distribution is narrower, and differs from the previously presented Maxwell distribution.

To explore the relationship between ion speed and operation power, an ideal nuclear reactor is assumed to be available, either fusion or fission based, that may deliver power at will, but of coursetotal energy is finite. The main question is how this energy can be used in order to provide maximum propulsion performance, in particular, maximizing the vehicle delta v. The calculations are using both energy conservation and the rocket equation. An energy range between 0.1 GWDay and 100 GWDay is used to provide an almost uniform exhaust velocity.

Ion propulsion seems to be among the most effective (with respect to fuel mass) propulsion systems, but concerning energy effectiveness (beam energy), the answer tends to become complicated and a tradeoff

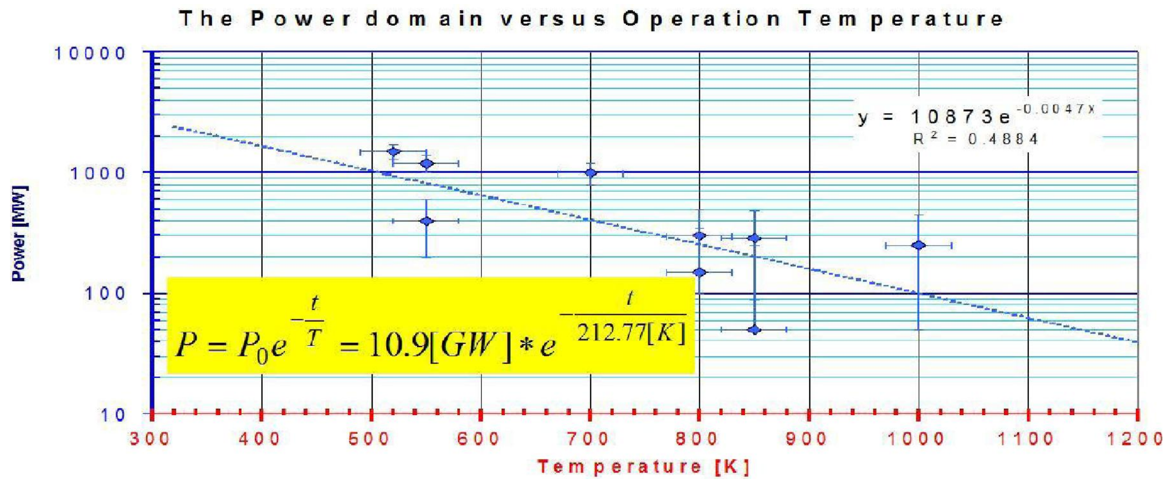


Figure 14 : Nuclear thermal propulsion benchmark figures

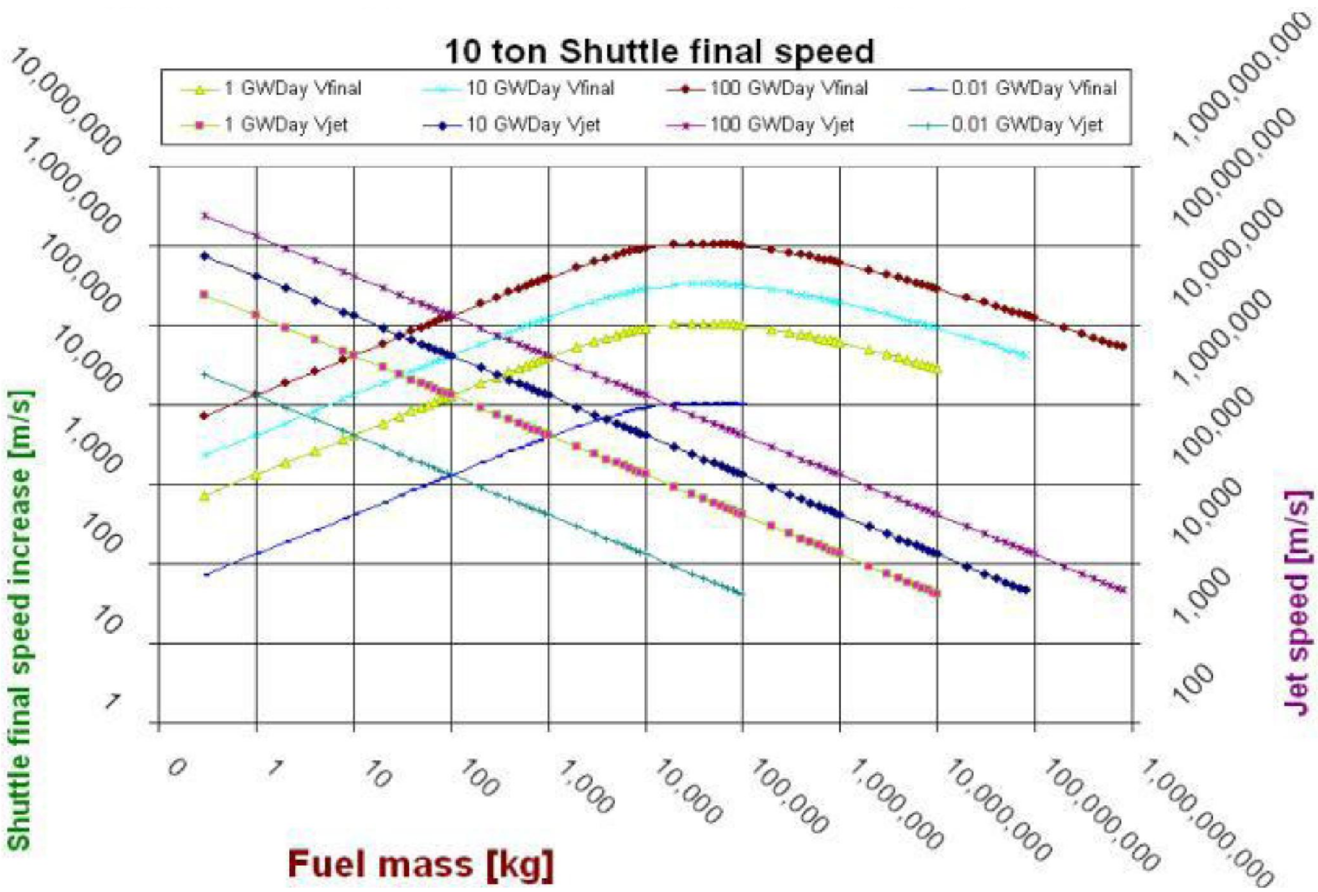


Figure 15 : The dependence of the final speed of a 10-ton shuttle on total jet mass and total jet energy

between ejected mass and associated energy becomes necessary.

The system considered is a nuclear-based electric power source that powers an accelerator like jet engine producing a mono-energetic jet. Under these circumstances, optimum performance is obtained when the ejected mass is 2.7 times the payload mass, but good results can be achieved in the range of 1 to 10 payload masses.

Figure 15 shows the spacecraft speed increase (left ordinate) as well as the exhaust velocity (right ordinate) plotted versus jet mass with total energy as parameter (see box above chart).

These data were used to calculate the potential (but unrealistic) travel time for a round-trip of a space vehicle from Earth to Alpha Centauri, starting from LEO (Low Earth Orbit).

For a 10-ton vehicle returned and parked in LEO, ten additional tons of fuel (hydrogen) are needed for the braking maneuver when coming back from Alpha Centauri, which results in a 20-ton vehicle mass during the ballistic flight phase. Hence, the mass of a vehicle that returns from a LPO (Low Planetary Orbit) at Alpha Centauri is about 20 tons, resulting in a total mass of 40 tons. However, additional fuel is needed for the braking phase when arriving in the Alpha Centauri system, driving the total mass up to 80 tons. Therefore, the total vehicle mass is brought up to 160 tons (LEO), because a similar acceleration phase is also needed at departure from Earth. This calculation is not really realistic, even for an automatic probe, since for such a mission a dry mass, including the reactor and thrusters, is not sufficient, but the assumption should be good enough to be correct within an order of magnitude, and thus provides a crude estimate.

CONCLUSIONS

Nuclear batteries – isotopic, fission, and fusion - are among the very few energy sources that are compact enough to assure extended space travel and might provide the possibility of colonizing our solar system from Venus to Jupiter, even including Pluto in the next two centuries. The first step will be Mars, the nearest and most life-friendly planet.

Novel radiation channeling devices open the way for more advanced shielding for biological life, electronics and other sensitive devices, as well as for radiation concentrators for energy harvesting or imaging.

The new developments of quantum-nuclear active environments, based on long-range nuclear reactions via entanglement, may open the way for better understanding of advanced concepts and power production.

Fusion-based devices are the only ones that do not have energy storage limitations in space, as is the case for fission and radioisotope based devices, delivering the best solution of generating power when required and producing an almost unlimited amount of energy, thus providing the most suitable power source for interplanetary travel.

Isotopic batteries are invaluable devices to power all kind of satellites, but, because of the half-life time of the respective isotopes, are the major cause for the limited life span of the satellite.

It was shown that those new devices developed by using nano-technologies in combination with nuclear technology, have many military and strategic applications. The opportunities created by this novel, powerful technology, which, by itself is not detrimental, may, however, become dangerous to mankind if applied by humans of insufficient moral qualities. In other words, it is indispensable that the advancement of technology is accompanied by a similar advancement of our civilization level that must take place at planetary scale.

The development of new thrusters in the form of electric, plasma, or accelerator based devices is pushing the limits for space travel. These new devices may allow for active flight trajectories that are beyond ballistic flight, and will substantially shorten the flight times to neighboring planets.

Advanced nuclear power, will remain the best availabe energy source for space, and if it will be augmented with advanced propulsion systems, it will make possible the travel with human crews outside the solar system.

Eventually, propellantless propulsion or field propulsion (a term introduced and discussed already in 1960 by W. R. Corliss [22]) (hopefully) might become reality.

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