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Advanced Space Nuclear Reactors from Fiction to Reality

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Abstract

The advanced nuclear power sources are used in a large variety of science fiction movies and novels, but their practical development is, still, in its early conceptual stages, some of the ideas being confirmed by collateral experiments. The novel reactor concept uses the direct conversion of nuclear energy into electricity, has electronic control of reactivity, being surrounded by a transmutation blanket and very thin shielding being small and light that at its very limit may be suitable to power an autonomously flying car. It also provides an improved fuel cycle producing minimal negative impact to environment. The key elements started to lose the fiction attributes, becoming viable actual concepts and goals for the developments to come, and on the possibility to achieve these objectives started to become more real because the theory shows that using the novel nano-technologies this novel reactor might be achievable in less than a century.

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1. Introduction

The development of the space applications requires exceptional power sources able to deliver enough reliable and at will energy to support activities during space flights and outposts. In the same time the power source have to be as small as possible, with fast response times, and self-contained. Only nuclear sources based on fission and fusion may successfully comply with these requirements but this technology is now at its early beginning in spite of about 100 years from its discovery. During this period enough elements come together to show that the time until mankind will achieve these power sources may not be so long, and if enough research will be committed it is possible that these exceptional power sources be deployed sooner than 2100. The ideal nuclear power source, generically called “fission battery” has to

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convert the nuclear energy directly into electricity and be light and safe to use in its near vicinity. The practice showed that it is possible to design small nuclear reactors, but shielding requirements make them bulky. Space nuclear reactors are mainly using a fast neutron spectrum that raises control related issues and thermo-mechano-electric conversion cycle that adds to the weight and requires sophisticated cooling systems.

The desire is to transform directly the nuclear energy into electricity, with high efficiency in order to minimize the cooling needs, and to have an ultra light shielding able to control all the functions in the reactor and safely shut it down in case of overheating or malfunction. The actual theory, computer simulations and experiments show that nano structures have the best chances to bring the direct energy conversion from theory to application. In the same time the 30 years of experience with radiation channeling showed that in the near future will be possible to trap in special engineered nano-structures like nano-tubes or nano-wires the high energy neutrons and gamma rays and guide them in the desired direction making a cloak for desired portions of space “shielding” them by denying trapped radiation the access into that space. More it is anticipated theoretically that controlling the transmission of the trapped particles along these nano-structures by an electro-sensitive element, there is possible to replace the actual nuclear reactor mechanical control system by an electronic one with response time in microseconds compatible with that of the prompt neutrons enhancing drastically the controllability of this nuclear power source. Other applications and by products are possible out-springs of this development.

The paper analysis of what have to be done to achieve the desired nuclear power source and of the actual state of art of the important technologies that have the capability to provide the necessary development.

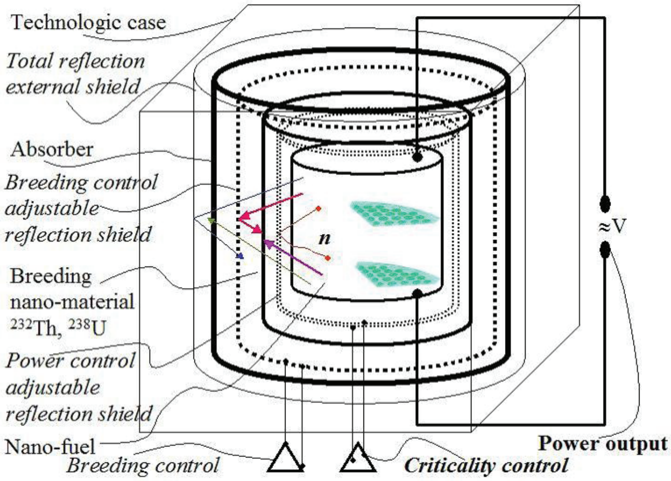


Figure 1. Compact, solid state nuclear reactor with direct generation of electricity from nuclear energy with electronic criticality control and ultra thin shielding.

2. Background On Advanced Nuclear Power Applications

The needed power source has to be lighter than several tones and generate several tenths to hundreds of MW being able to deliver more than several MWDay of electric energy at demand. The ability to deliver pulsed power is another plus. This kind of power source is a Generation 8 portable, compact, solid-state direct conversion nuclear reactor as shown in Figure 1.

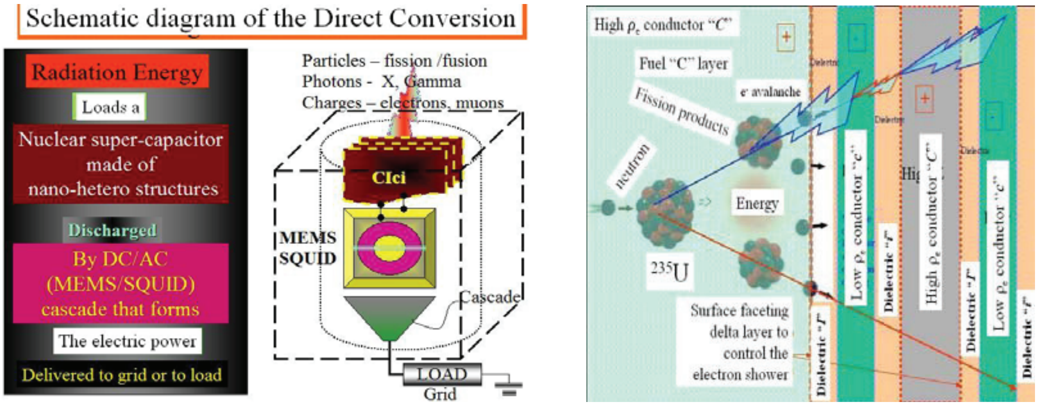
This reactor is based on two novel potential future developments that are actually in the concept phase:

- Direct nuclear energy conversion into electricity core made of nano-hetero structures
- Electronically controlled nono-guides for neutrons operating like control rods and shielding.

These two elements combined with a potential third element used to absorb the neutron excess and use into transmutation process or nuclear fuel breeding may drive to a 10 cubic feet nuclear reactor weighting about 2 tones able to deliver 100 MW continuous power for about 3 month and a pulsed power of several of GW for about few seconds, with high repetition rate.

2.1 Direct Nuclear Energy Conversion Into Electricity (DNECE)

DNECE relies on a nano-hetero-structure also called meta-material that forms a super-capacitor structure based on a repetitive nano-structure generically called “CIci” made of a high electron density conductor “C” insulated by a layer “I”, from a low electron density conductor “c” also insulator by a layer “i”, as shown in Figure 2(a) and 2(b). This super-capacitor is loaded directly by the radiation from inside, or in some cases produced externally, and is unloaded as electricity, adjusted by the inside structures at the right parameters to minimize the Joule effect and increase conversion efficiency.



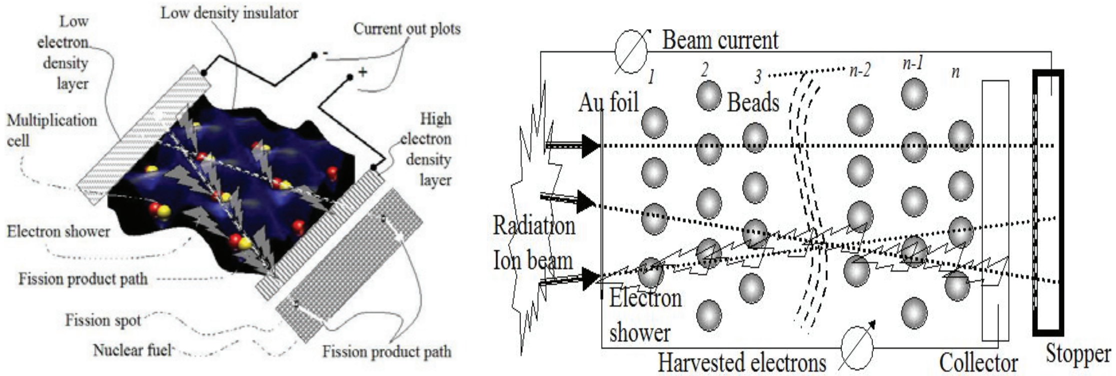
(a) **(b)**

Figure 2. (a) Operational diagram of direct generation of electricity from nuclear energy in a solid-state nuclear reactor, and (b) “CIci” operational diagram of direct generation of electricity from nuclear energy of the moving particles inside a meta-material planar structure

This is an alternative way to extract the nuclear energy, based on electricity flow instead of the actually used heat flow that limits the actual power density to less than 1 kW/cm^3. Meta-materials may provide a power flow even higher than 1 MW/cm^3, that drives to maximal power of about 200 GW for the above described reactor, but less than 1 day operation time. Removing the nuclear power as heat, the reactor structure operates cold, and even cryogenic supra-conductive structures may be designed.

Figure 2(b) shows a simplified “CIci” repetitive structure in order to present the physics involved in the direct extraction of nuclear energy as electricity. The neutron is colliding a fissile material say ^{235}U and triggers its fission. The fission products are sharing about 167MeV as kinetic energy, that allows them a path length up to 15 microns in urania are crossing the “CIci” structure training knock-on electron avalanches after them. The intense stopping in a high electron density material “C” is generating an intense electron shower that ballistic travels through the electric insulator “I” and stops in the low electron density conductor “c” polarizing it negatively. The fission product crossing the “c” layer produces a smaller up to eight times electron shower, which dims a little bit the accumulated negative charge. The conversion efficiency calculations on this basis set the limit at about 85%. Quantum effects come into play with capability of increasing even further the conversion efficiency, or dimming it.

In practice the meta-material will have a different form and shape as shown in part in Figure 3(a), being very near to quantum dots, and operating as a material opening to the knock-on electron shower and functioning as a dielectric in reverse, a kind of self loading diode. The dimensions of the elements involved in the process are in tens of nm where quantum and electronic ballistic effects are concurrent. This structure is being capable of delivering kV range voltages.



(a) **(b)**

Figure 3. (a) Robust nano-cluster based "CIci" meta-material, and (b) Modified "CIci" solid-state tile or battery element.

As a by-product of the nuclear reactor structure is the isotopic batteries. The limitation in radioisotope power makes these sources suitable for small batteries, with power in the range of 100 nW up to 100 W, and dimensions from 0.001 mm^3 to 1 liter. This makes them suitable for distributed sensor systems and micro-power-sources.

Figure 3(b) shows a nano-clustered direct conversion structure meta-material another version of the Figure 3(a) structure that is delivering higher voltage being robust to radiation damage, mechanical stress and temperature. It may work using outside beam or radiation or encapsulating radiation sources in order to have a high overall energy conversion efficiency

Once the production receipts are well defined the production of several cubic feet of nano-structure will represent an effort equal with less than 10% of the actual semiconductor industry capacity. The maturity level of this solution is TRL=3+ and coherent efforts are needed to develop a prototype and future materials. The delivery term for such power source may be earlier than 2030 if intensive researches are started today. An earlier byproduct is the DC-isotopic battery being equivalent in energy with more than 30,000 same size actual chemical batteries, that may revolutionize the electronic design of the long term, continuous usage electronic devices, like pace-makers, distributed micro-sensors, etc..

2.2 Advanced materials for shielding and beam power harvesting

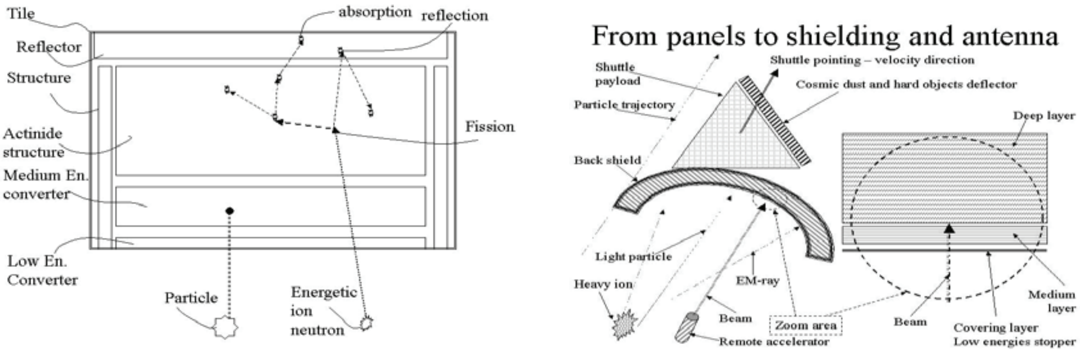
The same materials used to create a compact nuclear reactor structure may be used for shielding and beam-power harvesting. The nano-hetero- structures may be produced in layers with the properties customized on the radiation to harvest. High-energy protons and atoms require thicker substrates for example for 1 GeV protons about 4 inch of harvesting structure is needed.

This structure may be arranged in tiles, having the layers customized as in Figure 4(a). The first layer is a hard low energy conversion layer, harvesting EM radiation in optical and IR bands and few MeV protons and other heavy ions.

The second layer covers the particles energies domain from MeV to several hundred MeV, while the third layer may contain actinides to harvest neutrons energy as well to increase the stopping power for

GeV particles. The reflector turns back the secondary radiation, increasing the harvesting and shielding efficiency.

Figure 4(b) shows an application for space shielding-antenna to be used for remote beamed thrust and power transfer or for shielding against other beams or cosmic particles. Different from any other shielding this is a position-direction sensitive material that detects the particles direction and energy simultaneously with harvesting their energy. The use of pulsed power in space as laser devices or accelerators may generate a large variety of applications from remote power transfer to thrust and energy on board with power projection capability.



(a) **(b)**

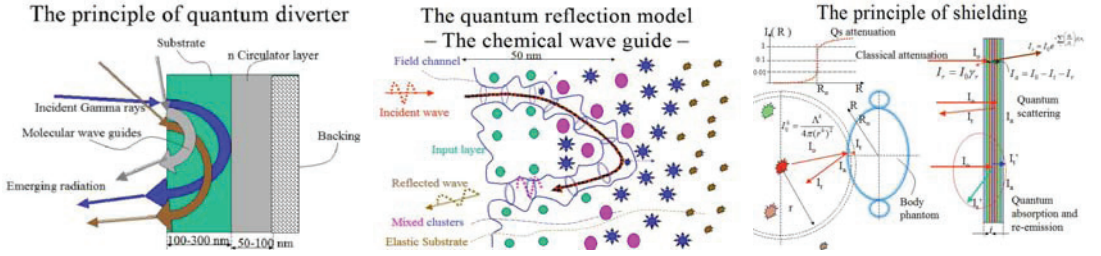
Figure 4. (a) Tile element with three functional layers, and (b) the use of tiles in shielding and remote thrust and energy transfer.

2.3 Radiation hardening based on nano-structured advanced materials

Another very important material for the future solid-state compact reactor is based on nano-structure radiation guiding layers. The radiation is trapped into a nano-structure that acts as a wave-guide by a collective nuclear interaction of the structure elements with the trapped particle and drives it along, gently turning it around and releasing backwards in the same direction it was coming or in a direction at choice.

Figure 5(a) shows the principle of such layer having curved micro-paths inside the micrometer thick substrate that turns around the radiation (gamma or neutrons) trapped inside the molecular wave-guides.

A neutron circulator layer, composed of an electro-sensitive material is controlling the transmission along the molecular wave-guide, by introducing the so-called quantum deflector material as shown in Figure 5(b). The quantum deflector acts like a binary or analogical switch, controlled by the electric field. In one state it leaves all the particles follow the molecular guide while in the other state it makes them lose the channel and switch on another path.



(a) **(b)** **(c)**

Figure 5. (a) NSRG Shielding and radiation control principle, (b) an atomistic artistic view of the Shielding principle, and (c) nano-guide.

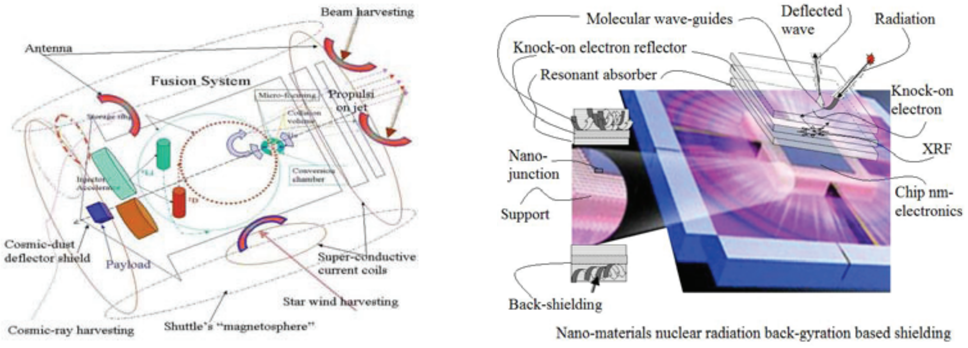
Figure 5(c) shows the three shielding possibilities offered by modern materials for the case of a human protection suit, in blue. The radiation dependence of radius inside the blue protected space is shown in up-left chart. In the right side is a rectangular section in the shielding multi-foil showing the mass absorption, than the quantum scattering inside guiding nano-structures, and the quantum resonant absorption and reemission of radiation, similar to Moessbauer effect. All these effects are used synergistically to create the super-shield, and the electro-active nuclear reactor control shield shown in Figure 1.

This shield regulates the criticality similar to a reflector but actuated electronically and having a response time in microseconds. When the quantum diverter is off, it returns all the neutrons in the core ant the power is increasing, while it is off the neutrons are scattered and are absorbed in the breeder blanket, that is surrounded by a shield that returns the neutrons in the breeder tangentially. This is the system that assures the ultra-short power pulses, and it may be aided by an accelerator to produce short time neutron excess needed to power a pulsed directed energy system.

2.4 Potential Applications And Their Importance

The application range of the combined solutions is very large, spanning from mini-power sources for MEMS satellites to complex very powerful hybrid power systems, and here there are few of them.

Figure 6(a) shows a complex space application based on direct conversion nano-hetero structures. Due to “critical mass” imposed limitations the fission power is limited in space to several TWDay or less, which means maximum several tens of tons of actinides might be placed on a shuttle without spontaneous criticality risk. When higher power are desired fusion systems are needed for which the storage of the primary products may be done without “fission criticality” restrictions. The main power system relies on super-colliders, with aneutronic fusion chamber, using a part of the fusion particles for jet propulsion, and external shield and antennas used for power and thrust exchange and protection.



(a) (b)

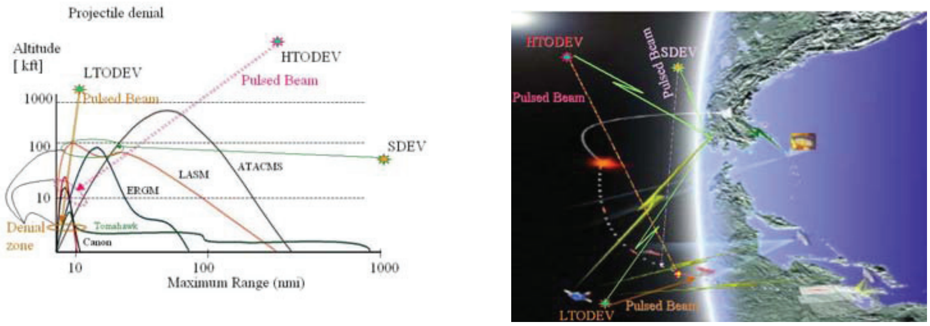
Figure 6. (a) Intergalactic space shuttle power system, and (b) super shielded micro-chip.

A cosmic ray energy-harvesting device based on funnel shaped FODO magnetic structures to shield the payload and increase the efficiency of the harvesting tiles creating shuttles magnetosphere is figured. Cosmic dust, high speed particulates agglomerates up to higher objects represents a problem for any space shuttle and special protection systems are needed to make the deflector shield.

Radiation Hardening by nano-shielding the sensitive parts in order to reduce the probability of single-event indisposition of nano-electronics, that comes to aid the fault tolerant, distributed parallel architectures. Figure 6(b) exemplifies how a combination of shielding principles and energy harvesting may prevent errors to be transmitted in nano-processors.

The nuclear reactor as described in Figure 1 will be a perfectly matched power source for many directed energy applications both in military and civil domain, being a game changing technology in defense.

From the military tactical point of view the use of directed energy may give tremendous advantages in denial even ballistic fire of an enemy side. Figure 7(a) shows the great change in interception and denial procedures by using pulsed beam directed energy systems. The range and height curves are given for US made devices, equivalent devices. The ATACMS (Advanced Tactical Missile System) and LASM (Land-Attack Standard Missile) have the biggest radar signature, but due to their high speed are difficult to intercept. The ERGM (Extended-Range (Gun) Guided Munitions) and canon munitions are harder to denial due to the fact that are flying in low atmosphere and have robust shell, requiring high power laser placed above the gun battery. This might be achieved using LTODEV (Low Terrestrial Orbit Directed Energy Vehicle System), with a good visibility over the battlefield carrying the IR Laser system. Beam systems are effective only in upper atmosphere and outer space. The HTODEV (High Terrestrial Orbit Directed Energy Vehicle System) is effective against ballistic missile systems flying in high atmosphere and LTO. The SDEV (Stratospheric Directed Energy Vehicle System) may fly thousands miles away from the enemy's launch pad having the capability to intercept and destroy the flying object as soon it exits the stratosphere.



(a) **(b)**

Figure 7. (a) Ballistic fire systems, and (b) exemplification of pulsed power advantage over the kinetic energy interceptors.

The great change in interception and denial capability with emphasis on ballistic missiles is shown in Figure 6(b). The actual procedure relies on launching an interceptor missile to meet the enemy's missile on its path, and blast it. It is a very difficult task because the objects are coming towards each other with a speed greater than 10 Mach, leaving very narrow tolerance for blast timing, and trajectories approach. The novel approach based on stratospheric airborne or Low or High terrestrial Orbit pulsed beam directed energy system may assure the denial in its first 10% of its path being more tolerant for timing. That is assuring a large time interval the enemy's ballistic missile can be destroyed by HTODEVs or SDEVs. A LTODEV placed on a geo-stationary orbit near the vertical of the enemy may deny even cannon medium distance shouts and almost all missile systems and airplanes flying in troposphere, as the ellipses in Figure 7(a) called "denial zone" shows. In this way the enemy's tactical space is reduced to less than 10,000 feet in altitude above its territory and almost all systems firing more than few miles can be denied obliging the temporary enemy towards more reasonable actions and peace negotiations. Other applications are in pulsed propulsion, earth anti-meteorite protection, space cleanup of debris, and obsolete satellites, neutrino communications, etc.

Up to here it sounds like science-fiction stuff, but almost all the components become objects of the actual research aiming to bring to life these applications already, the mentioned performances being the goals of these researches.

3 The Actual State Of The Art And Future Trends

The main elements needed to build up the structures described above are in the early stage of development:

a) Direct conversion – From Moseley cell [1] up to now there are 100 years of attempts to do it and the experience showed that nano-structures have the best chances to accomplish this.
b) Radiation guiding in nano-structures, debuted as radiation channeling 30 years ago, and the actual developments showed the capability of guiding neutrons and X-rays, by materials in super-mirrors used to guide cold neutron produced at spallation sources, and soft X-rays in synchrotron installations.

3.1 Evolution Of The Direct Conversion Of The Nuclear Energy Into Electricity Devices

The direct nuclear energy conversion to electricity concept appeared by 1913, when Moseley [1] first demonstrated the Beta Cell. The field received considerable research attention for applications requiring long-life power sources for space needs during the 50s and 60s. The scientific principles become known step-by-step, and modern nano-technology is likely to create new devices and interesting material properties not previously available.

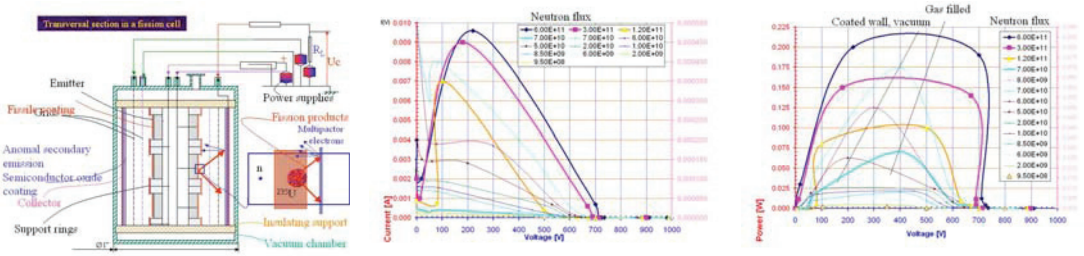
3.1.1 Charged Particles' Kinetic Energy Harvesting Devices

The interest in direct conversion reappeared in early 1940s, Kallmann [2], has measured the intensity of radiation of slow neutrons by means of an ionization chamber Ra-n-^{10}Be. Few years later Linder [3] developed the thermo-ionic fission, followed in 2000 by a study made by Polansky [4], Beller [5] and Brown [6], improving the concept by introducing the magnetic insulation, base on secondary multipactor electron suppression, by deflection in magnetic fields; it uses almost the same spherical structure as Moseley's beta cell [1].

The very same design was used by a Sandia-Los Alamos-Tel Aviv team [7] to design a nuclear battery based on the direct energy conversion of the fission products by using a nuclear reactor with ultra-thin fuel elements of 0.2 μm of ^{242m}Am. The amount of nuclear fuel is 376 g and the dimensions of the battery are 2.4×2.4×2.4 m^3 (including the vacuum spacing), with a BeO moderator and Be electrodes. The total power of the reactor is 10.6 MW and the electrical power is estimated at 0.652 MW, with an energy efficiency of about 7%. An improved design makes the fission result to be self-contained, in the current-producing ball, tube, or chamber with an anode and a cathode. Some of the concepts, such as the grapefruit-size ball called a Magnetically Insulated Fission Electric Cell, showed potential of mass manufacturability, and can be stacked together into arrays that could produce perhaps 60 megawatts of electricity, theoretically being capable of 60% conversion efficiencies. A cell the size of a golf ball might produce six times the energy of a D-cell battery.

Two years later, Broxon [8] build a differential ion chamber, observing the differences among electrode materials properties. It was Rappaport [9] who observed that inside nuclear reactors there is plenty of radiation and invented the nuclear batteries. From all the radiation inside a reactor the beta rays seamed the most easiest and direct approach, so Willson [10] developed a beta ray collecting cell, using a cylindrical geometry, depositing the beta emitter material on the central electrode, grouping his cells in bunches, and after two years Schwarz [11] beta-voltaic nuclear batteries and more particularly to batteries utilizing fission products as well as neutron activated isotopes of a reasonable half-life which deliver negative beta. A nuclear battery of this type comprises within a highly evacuated container, a solid beta emitter emitting negatively charged electrons and thereby acquiring a positive charge itself and a collector which is hit by the electron thereby charging the collector negatively. An electric field is thus being build up between emitter and collector.

In 1978, a Romanian team, lead by Ursu and Purica, patents a cell for producing electric energy from nuclear fission energy [12], shown in Figure 8(a). The cell uses a cylindrical geometry, having the fissile material deposited on the central electrode. It considers the multipactor effect and uses it to amplify the current by a combination of suppressor grids, material coatings and voltages, creating a kind of synergy [13]. The output parameters of different types of fission electric cells have been measured during their irradiation in the nuclear reactor of the Central Institute of Physics in Bucharest, Romania [14]), at different thermal neutron flux values in the 10^8 -10^{12} neutrons/cm^2 s range. These measurements allowed an estimate to what degree the output parameters depend on the n_{th} variation and pointed out the differences in the operation between gas and vacuum filled devices. Figure 8(b) is showing the current vs. voltage measured at the cells fulfilled with gas and without gases at different neutron fluxes inside the reactor VVR-1.



(a) (b) (c)

Figure 8. (a) Direct conversion cylindrical cell, (b) Current vs. voltage and neutron flux, and (c) Power vs. voltage and neutron flux.

Figures 8(c) shows the dependence of the output power of voltage and neutron fluxes. The thick curves with bigger marks are represented on the left scale corresponding to the gas filled cell while the thin line curves used mainly for guiding the eye are represented on the right scale and are for the vacuumed cell. Various types of gases combinations and pressures have been tested over the time, getting minor improvements in the power density. The conversion efficiency is under 25% because more than ½ of the fission products are lost due to geometry and more than ½ are lost in auto-absorption in the actinide coating. More elaborated versions have been designed containing multiple layers of cylindrical capacitors, similar to the Styrofoam capacities separated by vacuum, giving some increase in power density by up to 10 times and almost no increase in energy conversion efficiency. With all the progress this structure proved that has a power density lower by more than 100 times than the usual power density in the thermal reactors, exhibiting problems of mechanical stability and criticality. It was observed that making the uranium coating thinner the efficiency is increasing but the power density and local heat was decreasing.

In about the same period and geographic location the concept of direct energy conversion was first recognized by Budker [15], but it wasn't until 1967 Post [16] described a high efficiency multi-plate collector that serious study was given to it. In their view direct energy conversion was the conversion of charged particle kinetic energy to potential energy. Typically this is done by decelerating and collecting the charged particles on high-voltage plates. Extensive direct energy conversion engineering and economic studies were subsequently made by researchers at Lawrence Livermore Laboratory in the 1970s [17].

Direct energy conversion is particularly attractive for aneutronic fusion power plants since over 99% of its power are released as charged particles. Efficiencies of up to 80% may be achieved using direct energy conversion in nuclear fission reactors where about 167 MeV out of 203 MeV released by reaction represents kinetic energy of the fission products, in contrast to 40% efficiencies from conventional steam-turbine power plant designs. An interesting approach was the Venetian Blind direct energy converter concept developed at Lawrence Livermore Laboratory [18] uses ribbon-like surfaces that are more transparent to ions going forward than to ions going backward [19]. Ions pass through surfaces specially coated and processed [20] of successively increasing potential until they turn and start back. They then see opaque surfaces and are caught. In this manner, ions are sorted by energy with high-energy ions being caught on high-potential electrodes [21]. The solution for a direct energy conversion beam dump for a 1.6 MeV neutral beam with energy recovery was tested more recently for the International Thermonuclear Experimental Reactor [22] Cadarache in France.

By 2002, an University of Florida team developed the concept of a Direct Energy Conversion Fission Reactor Gaseous Core Reactor with Magneto-hydrodynamic (MHD) Generator [23].

3.1.2 Secondary Electron Shower Harvesting Devices)

In the same period Ritter [24] developed a radioisotope photoelectric generator for use as high voltage source that comprising alternating electrodes of high and low atomic number materials activated by photon-emitting radioisotope for producing electrical energy. The construction of the generator is similar to that of a well-known storage battery. The generator is composed of alternate layers of high-Z, (high atomic-number) and low-z (low atomic number) material, which are insulated by vacuum or other insulating material. Low-energy photons from a radioactive source interact predominantly with the high-Z material by the photoelectric process, ejecting photoelectrons whose energy extends up to the incident gamma-ray energy E. By selecting the high-Z material thickness to be less than one electron range (at energy E) and the low-Z material thickness to be more than one electron range, there is a net electron transfer from the high-Z plates to the low-Z plates because electrons are emitted predominantly from the high-Z plates and stop in the low-Z plates. After start-up, a potential difference will build up between the high-Z and low-Z plates. An upper limit for this potential difference in kilovolts is the energy E in keV. The high-Z plates are connected together electrically and the low-Z plates are connected together electrically thus forming a “battery. “ The “battery” delivers power to an external electrical load, preferably but not necessarily a resistor, whose value is chosen to maximize the power delivered to the electrical load, to yield the voltage desired, to control the temperature of the plates. This structure is similar to the “CIci” structure presented in Figure 2(b) above with the differences that not gamma but a large spectrum of moving nuclear entities may be used if appropriately customized.

3.1.3 Semiconductor devices

By 1950 was the boom of the transistor period and the start-up of the innovation in semiconductor devices, and Schuyler M. Christian 1958, introduced the Semiconductor metal junction in beta fluxes harvesting its charges. The development of semiconductor electronics brought novel developments in the batteries and Frederick [25] developed junction electron-voltaic semiconductor. He disclosed an electron-voltaic semiconductor power source comprising a semiconductor body with a PN junction terminating in a passivated channel on one surface of the device. A radioactive source with voltage less than the radiation damage threshold of the semiconductor is used to generate carriers within the semiconductor body and the entire device is shielded with a metal casing formed on the device surface which also serves as electrical contacts for the device, about the same as the actual beta batteries. A miniaturized nuclear battery, was disclosed by Adler [26] consisting of several in series connected cells, wherein each cell contains a support which acts as positive pole and which supports on one side a ß-emitter, above emitter is a radiation resisting insulation layer which is covered by an absorption layer, above which is a collector layer, and wherein the in series connected cells are disposed in an airtight case.

Yasuro [27] disclosed a device where radioactive energy is converted to electric energy by irradiating a converter body of semiconductor material etc. with radioactive rays to produce a number of electron-hole pairs in the converter, applying a magnetic field to the converter in a direction perpendicular to the direction of diffusion of the electron-hole pairs to separate the electrons and the holes in a direction perpendicular to the direction of diffusion of the electron-hole pairs and to the direction of application of the magnetic field and deriving the electrons and the holes from electrodes provided on the respective end faces of the converter body as electric energy.

Anthony Thomas R. Schenectady who patented a deep diode atomic battery made from a bulk semiconductor crystal containing three-dimensional arrays of columnar and lamellar P-N junctions made an early development resembling the actual MEMS devices. The battery is powered by gamma rays and x-ray emission from a radioactive source embedded in the interior of the semiconductor crystal.

Van Dine [28] patented the directed energy conversion of semiconductor by the directed energy fusion of a selective region of semiconductor layer to provide a conductive path through the layer. A conductive path is formed through a semiconductive layer through opposed electrodes by conversion of semiconductive region, for example, by a laser energy applied to change the structure in the region extending between the electrodes.

Young *et al*. [29] published, in 1997 and 1999, two patents about charged particle powered battery for electronic microcircuits and sensors that comprises at least, one primary energy source and a number of electrically connected cells. It looks like a development of 1979 Ritter's patent to create an improved high energy-density battery for producing continuous low-voltage electrical energy is powered by direct conversion of the kinetic energy of charged particles to electrical potentials. An improved battery comprises, at least, one primary energy source and a plurality of cells, each cell comprising a secondary electron emitter plate spaced apart from a collector plate. Cells are configured to maximize the number of relatively low-energy secondary electrons from the emitter plates, which reaches and is retained by collector plates. Heat production is minimized during efficient energy conversion of the relatively high-energy of primary charged particles to the lower energy but relatively high current capacity of large numbers of secondary electrons. Material work functions and Fermi levels of the emitters and the collectors are chosen to favor emission of secondary electrons from emitter plates and retention of secondary electrons impinging on a collector plate, thus increasing efficiency and reducing internal battery leakage currents. Relatively low cell voltages and low heat losses in the direct conversion process mean that the energy sources may be confined in relatively small packages suitable for powering, and mounting in close proximity to, electronic microcircuits and sensors.

The idea is further developed and miniaturized to create a micro-power generator [30] for operating electronic systems, comprises radio-isotope source interposed between electrodes A micro-power generator, comprises an electrically insulating substrate; a semiconductor layer affixed to the substrate; electrodes affixed to the semiconductor layer for collecting electrical charges emitted by a radioisotope source; a radio-isotope source interposed between the electrodes; and electrical circuitry operable coupled to the electrodes for transforming the electrical charges into a controlled output.

A novel type of tritium based beta battery was disclosed by Gadeken [31] who made an electric current generating apparatus e.g. energy cell, has deep pores with tritium gas that on decaying generates beta particle that enters n-type region where electrons and holes are created under influence of an electric field.

A micro-electromechanical systems (MEMS) piezoelectric converter relies on an activator for micromechanical power generator, and includes radioactive source material arranged on one of displaceable sections of deformable element, to emit charged particles was patented by [32] group. The prototype device uses a copper cantilever 2 centimeters long. Future nanofabricated versions could be smaller than one cubic millimeter [33]. A similar idea was used by Winston [34] develops an application of piezoelectric switch element that uses a tritium light source.

Blanchard [35] states that "nuclear power may not be going away, as some activists might hope, but it is scaling down", developing hair width-sized, nuclear-powered batteries for use with miniature electronic devices that might soon be used in cars and to monitor health and other miniature systems.

3.1.4 Liquid Semiconductor Devices

A very important issue in all the devices attempting to convert charged particles kinetic energy is the end of range damage inflicted by the particle's stopping process particularities. The damage is due mainly to stopping particle collisions with the lattice's nuclei that makes them recoil creating dislocation defects.

The liquids are insensitive to this defects there fore if appropriately contained may represent a solution for a radiation robust material structure.

Shanks [36] patented a nuclear battery employing a low level beta emitter - includes photovoltaic source capable of supplying a low level of energy for a relatively long period of time. The battery includes a low-energy beta emitter and phosphor dispersed sufficient proximate the beta emitter to capture the low energy betas before decay. A photovoltaic receptor is configured to have a peaked response near the wavelength of the photons emitted by the phosphor. In a preferred embodiment, the photovoltaic, phosphor and beta source are formed into flexible layers, which are rolled into a cylinder in order to maximize the capture of photons emitted by the beta-excited phosphor.

Snyder and Fleurial [37] disclosed an alpha-voltaic power source to be used in space and ocean exploration missions, that generates electric current through separate collection of ions and electrons produced through ionization of gallium liquid. It converts alpha-particle energy emitted by liquid gallium or other liquid medium to electricity for use in electrical systems. Electrons are freed by collision from neutral gallium atoms to provide gallium ions. The electrons migrate to a cathode while the gallium ions migrate to an anode. A current and/or voltage difference then arises between the cathode and anode because of the work function difference of the cathode and anode. Gallium atoms are regenerated by the receiving of electrons from the anode enabling the generation of additional electrons from additional alpha-particle collisions.

The Liquid Electronics Advanced Power Systems (LEAPS) was proposed by Tsang [38] from GTI and financed by United States Defense Advanced Research Projects Agency (DARPA) for research and development of a new technology for directly converting radiation energy to electricity. Americium 242 is created when americium 241 absorbs a neutron in “fast reactors”. Americium 241 exists in large quantities as a by-product of regular power reactors but the process that turns it into americium 242 is still expensive today.

A liquid semiconductor-based radioisotope micro-power source has been developed by a research group at Missouri university [39]. The semiconductor property of selenium was utilized along with a 166 MBq radioactive source of ^{35}S as elemental sulfur. Using a liquid semiconductor-based Schottky diode [40], electrical power was distinctively generated from the radioactive source. Energetic beta radiations in the liquid semiconductor can produce numerous electron hole pairs and create a potential drop. The measured power from the micro-battery is 16.2 nW with an open-circuit voltage of 899 mV and a short-circuit of 107.4 nA

As a remarkable result of TEC devices it is Yarygin [41] was proposed a silicon-germanium thermoelectric converters with the radial-ring geometry at 1700 K, operating near physical limits. After Hacsi [42], a radioisotope direct-charging battery, also known as an atomic battery, can normally be compared to a parallel-plate capacitor with a self-charging plate that generates a high DC voltage low current hard to use. More amazing is the fact that there is no thermodynamic heat conversion process occurring in the direct-charging nuclear battery, so the efficiency is not restricted to the Carnot bottleneck of temperature extremes. He developed a DC to mechanic work converter V-H Motor/Generator, based on Volta’s Hailstorm to rum a MEMS water-mill wheel.

All the direct conversion devices are static; having no moving parts, and are not using the thermal stage in energy transformation in the conversion process. Most of the devices are difficult to integrate into a fission structure mainly due to criticality requirements as well to thermal requirements and radiation damage issues.

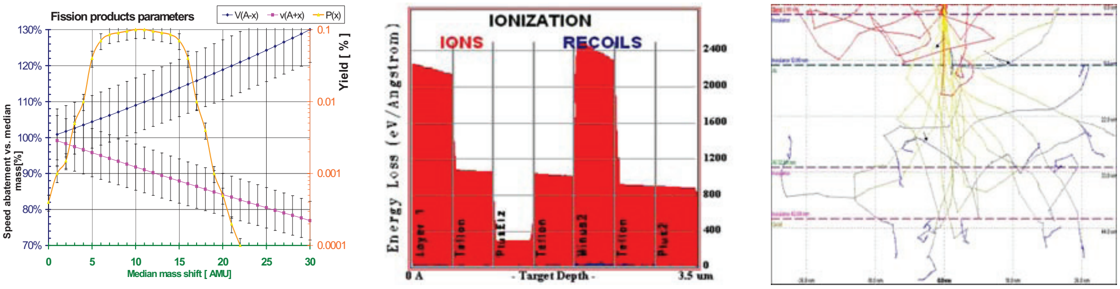
3.2 Some Predictions From The Actual Simulations

These developments show the growing interest to develop nuclear power and unleash its exceptional capabilities over a wide range of applications.

3.2.1 Fission Process Details

Analyzing and modeling the phenomena that are driving to nuclear fuel heating it is possible to acknowledge the complex interaction between the fission products and the fuel lattice. The knowledge about the first 1 μs of fission energy release, says that the balance [43] of about 167 MeV released, depending on instant process parameters, represents the total kinetic energy shared by the two fission products. This is the main energy, of about 80% of the total fission released energy that mainly drives to the fuel local heating.

Figure 9a shows a simplified model used for evaluation purposes only, which neglects all the fission process participants, as neutrons, gamma and neutrinos. It uses the conservation of energy and impulse to determine the fission products speeds and energies and, the yield curve to show that the effective fission products dispersion is contained in a domain of ±20% in the vicinity of median mass fission products.



(a) **(b)** **(c)**

Figure 9. (a) Speed and isotope distribution of the fission products, (b) Multi-material sandwich deposited energy by structure ionization and recoil, and (c) Electrons transport in "CIci" structure.

The fission products distribution is represented overlapped, on the median mass symmetry line (A=118 for ^{235}U fission), therefore the low masses densities of probability are about equal with the higher masses. The lower mass fission product has higher energy and speed than the higher mass resulted from the impulse conservation condition. The error sticks show that in reality the speeds are varying due to variance in neutrons parameters balance at fission act level. This qualitative observation mainly says that the range in materials is about the same and the concept of effective fission product thickness has to be introduced. Knowing from many theoretical and experimental sources that the stopping of the fission products in matter is done mainly by ionization, and only at the end of range the nuclear collision component becomes significant we may assume that knock-on electron generation is the process that stops the fission products taking from their kinetic energy. The simulation of the interaction (Zigler, 2008) shows that in urania sinter with no porosity fuel, the range is of 12μm for heavier than the half-mass isotopes and up 20 μm for the lighter ones. This stopping process takes several ps and in this small time interval there is no temperature in its classical thermodynamic sense, just energy redistribution from fission products to electrons.

Figure 2b shows in an artistic view the stopping of the fission products in a plurality of layers with various electron densities designated by material's "Z". It shows the trajectory of the simulation ^{135}Cs beam through the structure in the upper side, and the ionization energy deposition in each nano-layer in the lower side. The elemental composition of the nano-layers is irrelevant at this stage, but the rule of high electronic density, followed by an insulator than a conductor with low electron density and another insulator was followed. In the absence of any lateral conductivity through the nano-layers the electron-avalanches will travel a while along with the fission product leaving behind the holes, up to the moment when the polarization becomes strong enough makes them turn back by an electric breakdown. On these return moments they strongly interact with the lattice transferring it the energy and warming it up, creating the thermal spike. In order to prevent the heating we may put in contact the conductive layers and an organized current flow will occur among the layers depositing the power all along by Joules effect. Figure 9b shows the ionization power deposition into electron avalanches into a sequence of "CIci" layers of 500 nm thick. The first layer is Uranium, followed by PTFE and Aluminum, again PTFE, Gold, PTFE, Al, etc. The chart show that is an 8 times difference between ionization power deposition depending on conductor's electron density. Electron work functions, Fermi levels are secondary contributions to the process.

In order to prevent the fuel heating it is necessary to assure the energy removal from the structure before it starts to interfere with the lattice through appropriate conductors. The preliminary efficiency calculations show that values up to 90% are possible to obtain. One efficiency optimization criterion shows that the material design and thickness have to be made in such a way as all the energy to be lost by ionization in the high electron density conductor and almost nothing in the rest of materials. The other efficiency optimization criterion drives to adjusting the thickness of the materials of the optimal that may be crossed by low energy electrons as shows in Figure 9(c). As an indication about the thickness of the layers need to be used in the efficiency optimization process, similar to Young's patent that invoked the ballistic flight, inside the Debye length that is about several nm and is almost independent of the material type. These kinds of nano-layers are susceptible of being used to ameliorate the internal process kinematics without being visible in the energy deposition process, known under the generic name of δ layers. In reality is not quite so, very accurate nano-layer thickness optimization of material and interface is needed to be made in order to achieve the performance.

3.2.2 Nuclear Reactions Details

Radiation is the generic name for a large diversity of manifestations of the atomic and nuclear energy, but in fact the most important forms of radiation for direct energy conversion applications are those with short stopping range, driving to acceptable power density and good cost/performance ratio. From this point of view neutrons, gamma rays even X rays will not be considered for this application due to their low attenuation and low power density.

3.2.3 Fission

As a general rule all odd mass number actinides are fissile, while all even actinides are fertile. The most used for fission power production isotopes are ^{235}U and ^{239}Pu, but other isotopes as ^{233}U, ^{241}Am, ^{249}Cf, ^{251}Cf are good candidates for power production too. The fertile as ^{238}U, ^{242}Am exhibit fission cross-section mainly for energetic particles, therefore they can be used for fission too. The released energy is about 203 MeV/fission but only 167 MeV are found in kinetic energy of the fission products resulted from thermal n fission of ^{235}U, and are contributing to near-by structures output. The rest of the energy is traveling longer distances and may be lost or converted in other sell elements.

3.2.4 Fusion

Most of the useful actual fusion reactions ending by producing helium compound. The main problem of fusion energy conversion is that in most of the reaction some important part of energy is assigned to neutron (i.e. 14.1 MeV in D,T reaction). Aneutronic reactions as ^{6}Li-D giving two alpha particles of 11.4 MeV each, are the most likely to be efficiently used, but exhibits significant technical difficulties.

3.3 Nuclear particles interaction with matter

After more than a century of intensive researches it seems that the interaction of most of medium energy particles with matter may be characterized with sufficient accuracy by a Bethe-Bloch type of formula, similar to that used in Monte Carlo simulation software.

As the SRIM [44] simulation in Fig. 1 shows for medium energies (under 930 MeV) the dominant factor in the stopping power is the interaction with the electrons that produces the ionization of the matter, then towards the end of range the interaction with nuclei becomes important. The ionization power deposition is mainly dependent of the electron density of the structure crossed by the stopping particle, being very high compared to the initially exposed volume driving to huge temperatures, many times over melting and vaporization straight into the micro-plasma state, commonly called "thermal spike". The notion of temperature might have no meaning, in the form we commonly use in thermodynamics, all the process of stopping taking less than 100 ps, while the relaxation drives somewhere in microsecond domain. It is important to highlight that in spite the collision is almost all the time an electric force-field interaction, in the first 80% of the stopping path due to short interaction time the energy is transmitted to the electrons that are scattered while the nucleus is slightly displaced. During the last 20% of the stopping path, the particle speed is lower and the interaction time with the lattice nuclei becomes longer, transferring enough energy to create dislocation cascades with over 10,000 dislocated atoms.

3.4 The Thermal Spike

In usual nuclear fuels structures, as ceramic, metallic, or inert matrix, the knock-on electrons are transferring their energy to phonons, that locally producing high temperatures having as consequence the local melting and solidification of a narrow zone surrounding the particle path. In meta-materials there is possible to remove the huge ionization energy of about 20 KeV/nm by trapping the delta electrons as Figure 9b shows using a multi-layered alternate structure. That makes this part of the path to remain solid and at low temperature, while the micro-plasma state to be achieved only in the last 20% of the stopping path, making the reduced fission's thermal spike.

In this case the initial knock-on energetic electrons are sharing their energy with other electrons creating a shower that before dropping its energy to phonons and exciting the lattice vibration are removed and the energy is applied to an external electric load R_L. In the area of the micro-plasma volume, the dislocated atoms are losing the energy and recombining leaving behind a reduced number of dislocations, that can be further reduced by better engineered microstructures.

3.5 Nano-hetero structure issues

As shown in Figure 9b if there is the opportunity to remove the energy deposited by radiation as ionization before being shared with the lattice vibration modes, the thermal spike will not occur or will by drastically dimmed. To assure the electron extraction a polarization voltage is needed. To obtain polarization, different materials are needed for the layers. Figure 9b shows the ionization yield for 5 MeV alpha particles in various materials versus the normalized range. As shown in Figure 2b left side the optimal structure may be made from a combination of four layers, generically named "CIci" (Popa-Simil, 2007a-d). As Figure 9b shows the ionization energy deposition depends on the electron density specific to layer's material type and radiation type and energy. To have the ionization created electrons removed a part of the materials have to be conductors, separated by insulating layers.

3.6 The Delta Electrons

The first layer, exhibits high stopping power cross section to radiation having a lot of ionization energy dropped by the radiation, while the next three layers is desired to have no interaction with the radiation. The electrons leave the high electron density conductor "C", crossing the insulator material "I", and are collected by the low electron density conductor "c" that emits lower delta electrons shower, so it becomes polarized negatively by the difference of charge between what it receives and what it emits. At its turn it is insulated by layer "i" from the next structure high electron density layer "C".

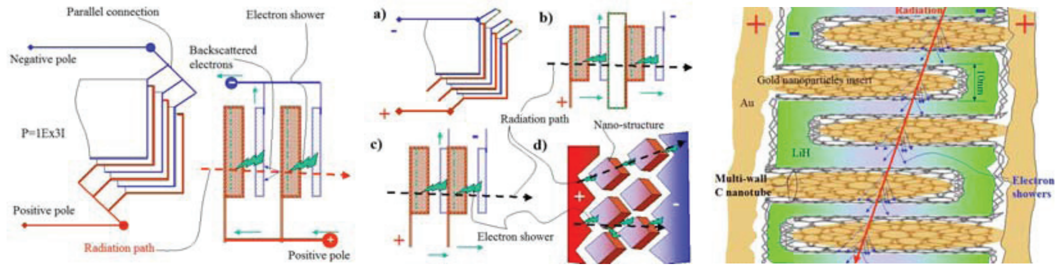
Figure 9(c) shows the density profile [45, 46] of the primary knock-on electrons produced by an energetic radiation in 10 nm of Gold layer, insulated by 20 nm of Silica from 20 nm of Aluminum insulated from the Gold substrate by 10 nm of Alumina. It is seen that the high energy (5 keV) electrons are passing through several repetitive structures giving most of their interaction in the in the high electron density material. The efficiency is given by the ratio between the total energy deposited and the energy of the collected electrons and applied to the load R_L. The statistic is low intentionally, to see the randomness of the path of each electron and its interactions.

3.6.1 Nano-Hetero Structure Details

The latest approach of Young *et al.* [29] resembles the planar capacitor structure, being mainly based on the difference of electronic emissivity between the internal capacitor armatures driving the polarization to the plots. The principle of operation is presented in Figure 10a. This kind of structure to be optimally built in order to provide high conversion efficiency has to match the electrodes dimensions with the dimensions of the armatures. The radiation crossing the capacitor armatures is knocking out electrons from the electron orbital. These delta electrons interact with the lattice producing more electrons and forming showers. If they are near the surface they may leave the metal foil armature and to cross the dielectric separator stopping in the next armature. If the armatures are made from different materials they exhibit different interaction cross sections producing different electron showers that gives different charge accumulation on the grids and polarization voltage occurs. This differential delta electron accumulation is the specific process that converts the interaction deposited energy by radiation into electricity.

3.6.2 The Optimization of the Harvested Voltage

The capacitance of 1 cm^2 of nano-capacitor is approximated as planar is of several microfarads for a 50 nm foil, being in super-capacitor class. The breakdown voltage may be estimated using as reference the value of 100 kV/cm for usual materials. Of course materials as Ta_2O_5 or RuO_2 [47] are showing better properties, but an estimated electric field operation value of 10 mV/nm is about right. Very few electronic devices may work well for a input voltage under 100 mV, and the usage of the parallel connection as presented in Figure 10(a) turns difficult. It turns that using a serial connection to add the voltages might be the best option that to conserve the high efficiency and to bring the output voltage into an acceptable domain.



(a) **(b)** **(c)**

Figure 10. (a) The principle of operation, (b) The serial connection evolution, and (c) MWCNT direct conversion advanced structure.

In Figure 10(b/*a*) it is shown the external connection of the multiple layers. This will drive to over-voltage in the last layers far from the radiation source due to ionization increase towards the end of the range, and makes ½ of insulator useless as shown in Figure 10(b/*b*). The optimal fabrication alternative is to produce bi-material grids as in Figure 10(b/*c*). The planar nano-layers exhibit a plurality of issues that makes them difficult to use. To produce a stable structure and taking the advantage that the middle grids are on floating potential there is possible to reshape the grids as small patches of nano-clusters passing through the electrons in a balanced manner to avoid breakdowns as shown in Figure 10(b/*d*).

3.6.3 The CNT potential use

The structural optimization applied to the harvesting structure has bed driven to a structure based on two robust electrodes, that contains a composite material made from an low density electrolyte and a plurality of nano-inserts with the role of making the electron flow distribution inside the electrolyte more uniform and to increase the number of electric charges while keeping the voltage at optimal values as Figure 3(a) shows. The equivalent capacities of such structures are reaching values in the domain of mF/cm^3 at several volts. One of the best constructive solutions to achieve higher conversion efficiencies as Figure 10(c) shows, is the usage of a special multi-wall carbon nanotube structure (MWCNT) immersed into a LiH electrolyte. Inside the nanotube the high electronic density material is trapped and uses the good conductivity to the lateral walls. The structure is similar to the actual advanced researches on enhanced double layer ultra-capacitors [48, 49].

3.6.4 The Power Density Limits

For a normal material breakdown limit and resistive losses in normal conductors the power density is up to 5 KVA/mm^3, which equals 5 GW/liter. At this power density, a structure with 25% fissile material embedded may run less than 1 day until is completely burned-out, but the real power density is in fact dictated the conversion efficiency. This means the structure must not heat-up over the upper limit, say for example to the melting or structure deterioration temperature. Therefore the energy that is not converted in electricity becomes heat inside the structure. Suppose the cooling heat flow may remove 1 W/mm^3 and have η=75% the total power density in the core will be 4 W/mm^3 from which 3 W/mm^3 is delivered as electricity. Cryogenic structures are anticipated to go at least 10 times higher in power density; thereby opening the way to a new type of miniaturized solid-state fission batteries and pulsed power sources.

3.6.5 Energy Harvesting Tiles

When it is assembled in tiles it harvests the energy released by fusion particles, ion beam alpha and beta irradiation or cosmic particles as shown in Figure 4(a). A version of this product is the isotopic battery that may have higher power density than the actual RTG devices. Due to the fact that most of the energy of the nuclear radiation is converted into electricity and removed as such less energy remains to be transformed into heat, therefore these structures are running much colder then the actual heat based devices. The higher the conversion efficiency is the colder the device runs. The released nuclear energy removal as electricity is much faster than its removal by heat making the power density values bigger by up to 4 orders of magnitude. The weak part of this solution is that it requires mass production of nanostructures, and is in the proof of concept and design stage. These direct energy power devices may have many applications in all the domains from space to surface. For space applications this structure may cut the payload by ½ for fission structures and by 90% for radioisotope power sources.

3.7 Summary

The thermo-mechanical intermediary conversion cycle is possible of being removed by a solid state-compact nuclear reactor battery that charges directly from nuclear fission energy and discharges it as electricity, as shown in Figure 1.

The development of the nano-hetero-structures using the knock-on electron showers may drive to compact high power nuclear structure harvesting fission or fusion energy. The direct nuclear-to-electric energy conversion relies on the controlled collection of knock-on electrons resulting from the movement of the nuclear particles inside a nano-structured lattice. Moreover, by having the energy extracted directly as electricity, there will be minimal to zero energy left for heating the reactor. Such a reactor will run cold, even cryogenic.

The harvesting efficiency is constructive structure dependent, from the over 90% unidirectional theoretically predicted efficiency, it decreases at less than 60% for the planar structure and isotropic radiation, increases a little for nano-clustered structures, and there is possible to further increase up to 80% for CNT hetero-structures. Real efficiencies may be even lower as directly depend on every constructive parameter, therefore only after building and testing a structure will be possible to get the exact values.

Direct nuclear energy conversion into electricity with applications in fission, fusion, hybrid structures, active shields and remote power antenna for space shuttles – without using thermal turbines and heat exchangers with efficiency possible of reaching over 80%. The nano-structure is made from many layers of Conductor-Insulator, has the advantage of removing the energy produced as electricity by a few orders of magnitude faster than by heat flow, which would provide exceptionally high power densities, up to several GW/liter from the actual < ½ MW/liter.

These structures are the most appropriate for space applications, producing the right amount of power for solar system manned exploration, and unmanned missions all the way to Alpha Centauri (Popa-Simil, 2005). The claim that nano-structure and electrical components can survive in radiation field is yet to be proven, because, radiation environments tend to destroy those components. Inducing fissions will ultimately destroy nano-structures. This might be a limiting factor.

3.8 From Radiation Channeling to nuclear radiation guiding devices

Starting since 1974 when the possibility of channeling radiation into the crystals was identified by Spiller and Segmuller [50, 51] many researches have been made with publications in more than 30 Journals, and more than 180 contributors, by 2008, but now their number have doubled. The main topics of interest [52] is covering fields like:

- Coherent scattering of relativistic charged particles in matter,
- Radiation of relativistic charged particles in periodic structures (coherent bremsstrahlung, channeling radiation, resonant transition radiation, diffraction radiation, parametric x-ray radiation, LPM effect)
- Crystal channeling, volume capture and crystal reflection of positive ions: theory and experiments; crystal assisted collimation in hadron colliders
- Channeling of radiations in capillary systems (micro- and nano-channeling, nanotubes, nanoporous), with applications (bending of the beams, positron sources, powerful radiation sources, x-ray waveguides, capillary/polycapillary optics, etc.)

3.9 Nano-tubes are similar to wave-guides

There are well known the applications of optic cables for data transmission as well the wave-guides for microwave power transmission for radar and microwave heating. Both cases well operation relies on reflection on the wall while the X and gamma uses Bragg reflection.

3.9.1 Microwaves and T-Rays wave guides

The admittance condition for the propagation in a wave-guide is says that the wavelength to be smaller than any geometric combination of wave-guide dimensions. Another condition is given by the wall conductivity that have to exhibit a smaller than 1/10 λ skin depth, and a low resistance so the attenuation coefficient to remain small.

The carbon nanotube almost meets these criteria [53], but to be a useful optical device it is also very important to control the input and output of the wave from the tube, that resembles mainly to aperture antenna. Phase and phase shift is an important factor in optical devices to give a coherent bright signal.

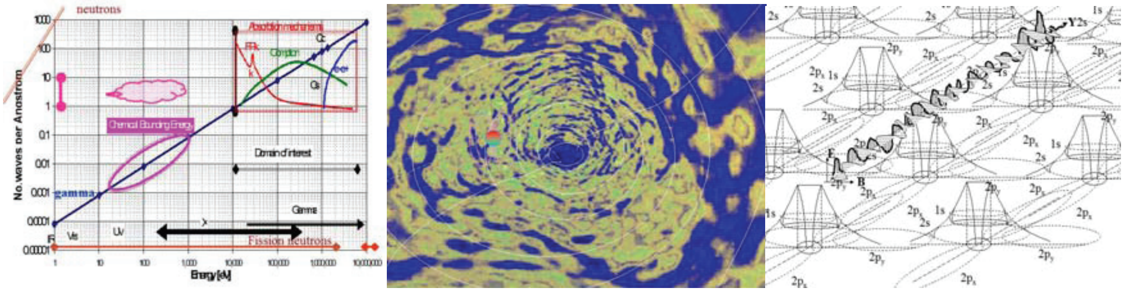
3.10 Potential nuclear applications of radiation steering in nanotubes

Last 35 years of radiation channeling researches and mainly during the last decade when the nanotubes and nanostructures had shown the possibility of steering the radiation in this structure in a controlled manner [54, 55].

3.10.1 From soft X-rays and cold neutrons to high energy X, Gamma, n diverters

To bend the radiation there is necessary to have an efficient enough interaction mechanism between the structure and the radiation. The Bragg or Fresnel reflection is one of the most common [54, 56]. Neutrons have even less interaction with the electron clouds, but they interact with the nuclei [57, 58] and magnetic gradients due to their magnetic moment , [59, 60].

Figure 5(a) shows the principle of the nuclear channeling [61-64], based on nanostructures that bends the radiation with more than 90 degrees. These structures generically called “radiation diverters” similar to microwave gyrators are based on the interaction of the radiation with the nanotube structures. For soft gamma and thermal neutrons the Bragg reflections works well enough. The radiation having a DeBroglie associated wave, long enough is interacting with the electronic discrete potential giving a path finding interference as Figure 11(c) shows that makes the wave stay and follow the channel.



(a) **(b)** **(c)**

Figure 11. (a) n,γ wave number versus energy, (b). Particle guided in a nano-tube, and (c) Collective path-finding self-interference.

The neutrons not having an electromagnetic wave associated interacts through the magnetic dipole [59] and nuclear scattering [65]. Combined multilayer carbon-nanotubes exhibiting variable magnetic field similar to a FODO (focusing-defocusing) structure used in the actual accelerators might the most efficient high-energy radiation-bending device.

Figure 11(b) shows a neutron traveling inside a carbon-nanotube. The red green sphere symbolizes the neutron magnetic dipolar moment while the light green-blue spots on the inner tube channel symbolizes the possible magnetic gradients of the atomic orbital of Carbon bounds and inner structure. The dimensional vibration due to temperature is about few femtometers is less than 1% of the molecular bound that may be about 1.36-1.41Angstrom. To have a wave length equal with the inter-atomic distance requires energy of few meV for neutrons (cold neutrons) and few keV for X Rays (soft). For energies greater than these, the moving entity has an associated wave looking like in Figure 11(c), when moves inside a lattice. The higher order mode resonance may occur in stable cryogenic structures that have a reduced thermal vibration. In normal structures only the gradient cylindrical symmetry of the magneto-electric force fields is what generates the stability of the moving entity trajectory in the middle of the channeling structure.

The challenge for the future development is shown in Fig. 11(a), that shows the correlation between energy and wave number in waves per Angstrom, for gamma and neutrons. This shows that for the energies of interest of several MeV for both gamma and neutrons the associated wave number is several orders of magnitude higher than the lattice atomic distance reducing drastically the probabilities of interaction, and collective interaction effects should be developed in order to have a successful high-energy radiation channeling effect.

3.11 Focusing and imaging devices

A special interest in research has been given to these devices [52, 66, 67] mainly used in space applications and medicine.

3.12 Personal shielding

The principles of personal shielding are presented in Figure 5(c) as an exemplification to ALARA. The various radioactive sources in the left are irradiating the body in section that is protected by a shielding material that dims the radiation by tenth of dB. The right side is showing the three known methods of dimming the radiation. Up right the mass absorption law, that drives to about 1 ton suit for upper body shielding [61 – 64] at ^{60}Co. Milimetric thick raincoat like based on quantum scattering in nanotubes, is only theoretically predicted. The quantum absorption and re-emission layers similar to Moessbauer effect may dim up to 6 dB the radiation.

3.13 Space shuttles ultra light shielding

The radiation shielding on space shuttles needs to be similar to those offered by Earth atmosphere that is equivalent of a 2 m thick lead wall but at 0.1% of the weight. Modified carbon nanotubes to present enhanced angular input acceptance are exhibiting the best chances for successful application. These may be developed such as to present no or little radiation reflection, focusing the emerging radiation towards energy harvesting structures.

3.13.1 Ultra light shielding

The complex gamma, neutron shielding formed by multiple wall carbon-nanotube structure might be used to reduce the weight of the actual nuclear reactor shielding. The only theoretic predictions that show the process is possible are not enough and the repetitive structure surrounding the nanotube as secondary layer have to pass through complete experimental tests. The development of this n, gamma channeling applications [58, 61 – 64] may have extraordinary impact on the future of the nuclear power applications. Even due to the development in structure, power density the nuclear reactors will become smaller. Potable nuclear power applications will not be fully accessible without lightweight advanced shielding.

3.14 Active nuclear radiation gyrators

It was predicted the possibility of driving the radiation through carbon nanotubes and porous structures [67 – 70] towards higher levels of complexity. The usage of piezo-electric, or ferro/ magneto-electric materials is susceptible to modify the propagation inside the nanochannel following an external electric signal. This possibility of controlling the radiation trapped inside the tube by the electric signals opens large possibilities for active radiation controlling devices a development similar to optoelectronics.

3.15 Electronic Albedo Control

Using piezo or magneto electric materials inserted [61 – 64] nearby the carbon nanotubes steering the neutrons makes that neutrons escape the nano-tube due to geometry variation that makes the grazing reflection not working. This kind of device acting over the escape neutrons from a nuclear charge may make it critical or sub-critical under the voltage control.

The response function for a single neutron is a step function, with two states "On" and "Off", while in statistic domain it may behave as a continuous transition function driven by the voltage. The importance of such a device is tremendous because it replaces the reactor mechanical criticality control by rods assuring in the same time the safety. Over passing a certain temperature the nano-tube property of steering the neutrons will be lost and the assembly becomes sub-critical.

3.16 Summary

The available information from literature and patents show a power law trend in generation of results in both the nano-technology and in its applications towards radiation guiding. If by 2005 the authors realized the capability of nanotubes to guide neutrons and gamma rays, today some experiments are done, with encouraging results. In what concerns the needed development to acquire the super shielding, and electronic control of criticality in nuclear reactors, important work still remained to be done. Our efforts are focused in developing the theory and the simulations in order to better predict the most appropriate nano-materials to be engineered in order to develop a controlled nano-guide radiation transport.

4 Conclusions

The purpose of the current paper was to analyze the state of the art and knowledge needed to deliver a compact, solid-state fission battery – nuclear reactor – and to figure out the possible roadmap to test and build that structure that now, in spite it is in TRL-2-3 it is still seen as a fiction. It was also to highlight that the research is very challenging, being over the most nuclear endeavors the mankind experience up to date, but with outstanding results, bringing the use of nuclear fission power near its technologic limits.

The theory and computer simulations showed that this structure is possible to be made in reality, if some supplementary technologic gaps are fulfilled, and a significant effort is made, delivering the capability of having unrestricted energy on demand in a large variety of space applications.

The experience of near 100 years of direct conversion and over 35 years of radiation channeling developments, their accelerated trend of delivering new results following a power law, shows us that all the knowledge required to build the dream nuclear reactor from Figure 1 might be available in less than 100 years, and the race started. The future advanced power structure might not be as cheap as the advanced thermal reactors, and might require isotopic enriched fuels, but its outstanding performances in space applications and beyond makes it a high importance strategic objective. It turns reasonable to intensify the work in research oriented in bridging the gap between the actual simulations and theoretical predictions and the experiments needed to build and deploy such structures.

Acronyms

CIci -	Conductor with high electron density, Insulator, conductor with low electron density, insulator
DNECE -	Direct Nuclear Energy Conversion into Electricity

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