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Bio-Inspired Wall Materials for Fusion Reactors and Transmutators

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Abstract

We present a set of suggestions to design and manufacture the first wall of a fusion reactor and a transmutation reactor (Transmutator), both of which tackle with the current energy crisis, based on a bio-inspired material. We isolate the first wall functions here from the rest of secondary walls. It will use carbon-based materials since neutrons and hard radiations do little affect the state of carbon materials. The multi-functional material should be thin enough so nearly all neutrons and gamma rays will go through the material without damaging its structure. Candidates are fibers or mats of Carbon Nano Tubes (CNT) or Graphene Layers (GL).

An important function to be added to the material is the cooling of the wall. The molten salt FLiBe is at 640°C. The wall could be cooled by a fluid going through the CNT fibers or the Graphene layers by capillarity. On the other hand, the first wall of a fusion reactors should face severe X-ray irradiation so that it should be of low-Z materials with thin enough not to absorb them, while it should serve separation of the vacuum for the plasma and the outer air.

Keywords: Carbon, carbon nano-tubes (CNT), graphene, radiation, bio-inspiration, capillary pressure, nuclear reactor, transmutation, fusion first wall

1. Introduction

We are facing the contemporary challenges of the impacts of human activities such as the climate change induced by the increase of CO₂ emission since the Industrial Revolution. The nuclear approach is a way to remedy this situation, both the fission-based and fusion-based. One of the challenges of fission nuclear path is its radioactive spent nuclear waste that can accumulate for more than the civilizational epoch (1). The fusion challenge is even greater. Recent years have seen a culmination of projects to design and build a fusion reactor. The Norman Rostoker's aneutronic fusion approach driven by beam injection have raised great expectations among the scientific community of fusion scientists (2).

It appears that a critical issue common to these new kinds of reactors is materials. Common materials such as metals or ceramics are not adequate to fulfil all the requirements of designers. So there is a great need to imagine new families of materials able to meet the challenge of these reactors. Intensive research in the field of multiscale design of artificial material are on their way. Material by design is a concept where a material is built from nanoscale to macroscale in order to meet all the requirements of the designer's specification sheet. This was made possible by the progress of material modelling. At the atomic scale codes using density function theory (DFT) (3) and (4) have paved the way to predict properties of materials which had never been created before. For the quantum design, ABINIT is an open-source code and probably one of the most widely used DFT code (5). The drawback of DFT codes is that they require high performance capacity of calculation. Another promising technique for the search of new material. The next scale is nanoscale where nano particles can enhance the global properties of materials. The particular approach we use is to create a network of different nanoparticles in order to obtain the desired properties of the material.

This work is, in part, a contribution to the design and realization of a carbon-based bio-inspired material for the first wall of a Molten Salt Reactor (MSR) generally called SMR (Small and Medium Reactor). The goal of the reactor is to eliminate the long-life nuclear elements from the nuclear waste which are the minor actinides mainly Curium, Neptunium, Americium. Neutronic transmutation of the spent fuel will reduce the amount of trans-uranium elements in the molten salt. In another part we consider the first wall of a fusion reactor, which emit high energy photons as well as other radiations (which could be mitigated to an extent by adopting an aneutronic fuel (2)).

Radiations in a reactor can be also used to reduce anthropogenic CO₂ gases and thus contribute to close the cycle of carbon in an opportune manner.

2. Fusion reactors and Transmutators

Though the nuclear energy production is in principle (or directly, if not indirectly) insulated from the CO₂ production, we have not achieved the treatment of radioactive waste production associated with the nuclear energy production, which could leave its impact as long as millions of years on Earth. We note that there is a sharp distinction between the fossil energy vs. nuclear energy, beside the sources of their respective fuels. That is the energy level, i.e. chemistry energy vs. nucleus energy: The former is based on the eV physics, while the later involves the MeV physics. We recognize some implications arising from this fundamental distinction and we will touch on it at least briefly to see how we can take advantage of its advantages and try to avoid its difficulties as much as possible. This means that while the “toilet science” of the fossil energy is also in eV, while that of the nuclear energy has to be also in MeV.

The genius and no-nonsense pioneer spirit of Professor Norman Rostoker was honestly, sincerely, and alertly picked up those issues that were brought up in the “Geneva Conference” at his core thinking and research topics. That is both the safe fusion as well as collective plasma accelerators brought up at the Conference. He recognized early both the power and danger of the nuclear energy properly and deeply, i.e. the sensible understanding of the nuclear MeV range of energy release in nuclear reactions. If such energy is mainly in neutrons, the MeV energies of neutrons is not easy to handle and can be even dangerous. Thus, he came up with aneutronic fusion idea. This way, implicitly (or explicitly) the downstream side of the issues is nearly all alleviated. Another point of the reaching MeV energy, according to Rostoker is to use accelerators to lift the particle energies up, thus resulting in the accelerator-driven fusion. Once MeV ranged neutrons are absent, we are to handle MeV charged particles and photons, which have much larger cross-section with matter’s charged particles and interactions to handle and less radio-toxicity to induce radioactive elements with long life times. This aneutronic path, nonetheless, leaves us to find proper handle of MeV charged particles and photons. Thus, it is of crucial importance to address a novel first wall concept that needs to confront the issues of handling MeV physics and chemistry. With this, we would finally reconcile or realize Norman’s ideal. Touching on the second item, i.e., Veksler’s inspiration, he was also among the earliest to search for more compact and collective accelerators using plasma. In this article, we develop our concepts benefitting from Rostoker’s aneutronic accelerator-driven fusion (2), (6), and fusion reactor-based neutron production (7) as well as collective plasma accelerators that can help driven fusion neutrons effectively to incinerate radioactive nuclear wastes. We need not further enter this topic, as the paper (1) addresses this. The neutron production methods that contribute to transmutation are discussed in more detail and we dwell on a particular method here in the present paper.

The aneutronic fusion reactors based on Rostoker’s vision (6) (and the reference therein) can avoid the severe materials issues arising from high flux of neutron bombardment, which could cause, among other things, the transmutation of the wall materials into radioactive ones as well as to avoid the quenching of the superconducting currents in the magnets (8), (9) and (10). Even the first

wall of fusion reactors based on such aneutronic fuel fusion reactors, much smaller but finite neutron flux is expected. Therefore, we need to look for the first wall that can best handle this situation. On the other hand, such burning of aneutronic fuel should cause a plenty of high energy photonics, as mentioned above. This is a major challenge on the first wall of an aneutronic fusion reactor. This leads to a consideration of various materials, as seen in Table 1. One way to avoid the high energy X-rays to heat and melt the first wall is, among other considerations,

- (i) to make the first wall made up with low-Z materials,
- (ii) to make it thin enough so that it does not absorb too much radiative energy,
- (iii) to choose the materials with high heat conductivity.

Materials	Neutron damage [dpa/yr]*, **	Neutron activation [Bq/cm ³]*	Corrosion	Physical properties
Stainless Steel 304	1	2.0124 10 ¹¹	53 μm/yr [2]	Hardness =140 kg/mm ² Melting point=1400 C
Inconel 601	0.9	5.2081 10 ¹⁰	> 34 μm/yr [2]	77 kg/mm ² [5] 1400 C
Hastelloy-N	1.2	1.6824 10 ¹¹	8 μm/yr [2] Corr. attacks Cr [3]	60 kg/mm ² [6] 1320 C
Carbon composites	0.12 Maintained structural integrity up to 32 dpa [1]	1.1959 10⁹	Extremely low – nm/yr? [4]	2600 kg/mm² [8] 2700 C
Graphite (reactor grade graphite)	0.0013	1.6358 10³	No attack by salt [p. 129 of 3] 2.5 years of operation	Low < 40 kg/mm ² [7] 3600 C
Diamond	Very low (for detectors) No data for wall, but should be even better!	Only fast neutrons , in reaction n+ ¹² C->alpha+ ⁹ Be	No data on corrosion. Extremely chemical inert	Please see othersSlides

Table 1 - Comparison of materials' physical and chemical properties in harsh radiative environment of fusion reactors and transmutators. We compare first three metallic candidates with the latter three carbon-based ones. Diamond and graphite provide chemical stability, low neutron activation and low neutron damage

As to the transmutator, the requirements are different, but also equally challenging (1). The reason for partitioning and transmutation of the Spent Nuclear Fuels or SNF is shown in Figure 1. A measure of the hazards from SNF elements is provided by the *toxicity*, and in particular the *radiotoxicity* arising from their radioactive nature rather than their chemical form. A reference point is the radiotoxicity associated with the raw material used to fabricate 1 ton of enriched uranium, including not only the uranium isotopes, but also all of their radioactive progenies. The radiotoxicity of the Fission Products or FPs dominates the total radiotoxicity during the first 100 years. Long-term radiotoxicity is dominated solely by actinides, mainly plutonium and americium isotopes.

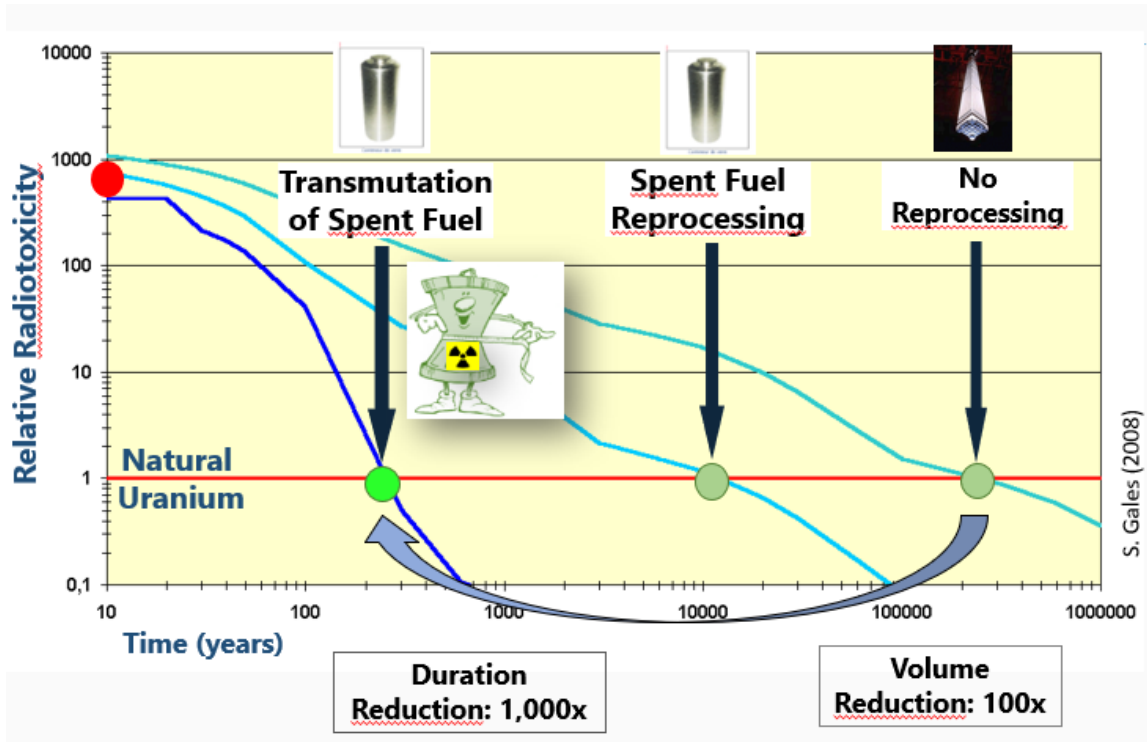


Fig. 1 Variation of the radiotoxicity of various products of spent nuclear fuels produced from nuclear fission reactors function of time for various treatment strategy. Transmutation can reduce drastically the duration of the decay and the volume by two or three orders of magnitude

The reference radiotoxicity level is reached by SNF after periods of more than 100,000 years. In more detail, the radiotoxicity of FPs dominates the first 100 years after discharge and decreases to the natural reference level in about 300 years. However, in the longer term, the radiotoxicity is mainly dominated by transuranic (TRUs), particularly Plutonium isotopes and decay products of Pu-241. Approximately 100–1000 years after fuel discharge, the radiotoxicity is dominated by Am-241, the radioactive daughter of Pu-241, with a level of about 3×10^7 Sv/ton U, i.e., about 300 times as large as the natural reference. Between 1000 and 10,000 years, radiotoxicity is dominated by Pu-240, with a value of about 4×10^6 Sv/ton U. Thereafter, Pu-239 is the main contributor to radiotoxicity with a value of 2×10^6 Sv/ton U. Beyond 100,000 years, the total radiotoxicity decays to the level of 10^5 Sv/ton U. After that, the main sources of radiotoxicity come from the descendants of Am-241.

The purpose of the partitioning and transmutation strategy is to artificially decrease the long-term radiotoxicity by irradiating TRUs in a neutron field. This is done by transforming the long-lived TRUs into short-lived fission products and thus reducing the necessary storage from 100,000s years to 100s of years. Furthermore, the volume of the storage is also drastically reduced due to the reduced overall volume of the SNF but also due to the reduction in heat emitted by the SNF.

3. The molten salt transmutator

The transmutator uses a liquid fuel composed of TRU dissolved in a suitable molten salt media (e.g. mixture of lithium fluoride (LiF) and beryllium fluoride (BeF₂)- FLiBe). The neutron generation method in the in-situ molten salt with dissolved transuranic is an elegant and simple approach to induce electron-generated gamma photons, which in turn generate neutrons, which are the instrument for transmutation. In addition to this simplicity and integral nature of the operation to generate neutrons, this allows the use of a real-time passive and active monitoring (11) via spectroscopy and consequent

feedback control of the TRUs refuelling, reprocessing, and criticality further coupled with the monitoring of the distributed neutron sources. See Figure 2.

Feedback control by Artificial Intelligence

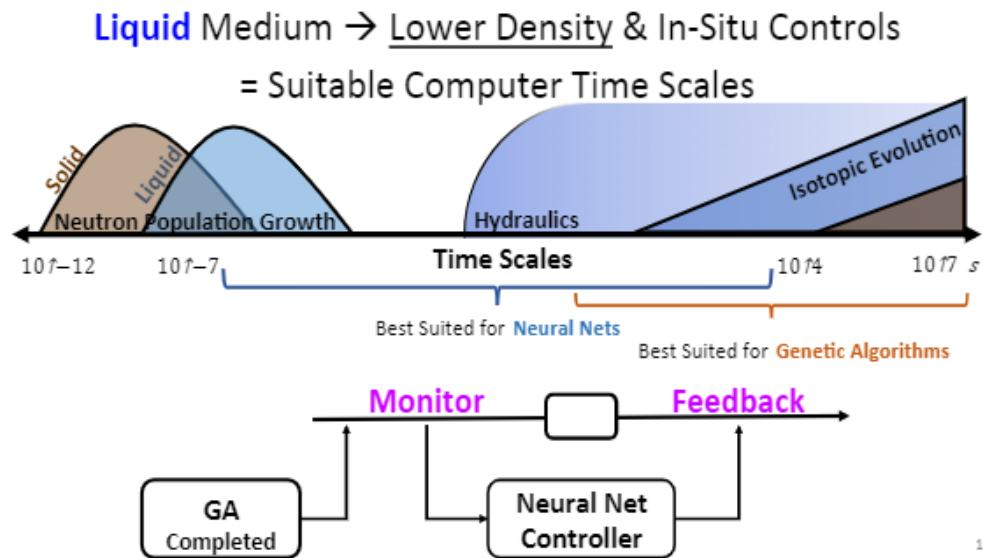


Fig. 2 The opportunity for the feedback control in the liquid molten salt. The hierarchy of the time scales of the transmutator based on the liquid molten salt are not as disparate as in solid-operation for the purpose of feedback functions (nuclear type of interactions vs. hydrodynamic interactions).

The active spectroscopy may be enabled by laser pulse passing and interacting with the liquid and its constituents and providing valuable spectroscopic information; our attempt is to go beyond the current technology with solid fuel rods whose physical and chemical condition is not easy to monitor during the operation. The passive spectroscopy collects emitted gamma photons from decay of radioisotopes. The spectroscopy and monitoring can be done real-time and *in-situ* or in batch mode for passive gamma spectroscopy. In addition, an active gamma spectroscopy may be adopted relying on the nuclear resonance fluorescence (NRF) to collect data pertaining to the isotopic composition (e.g., the NRF is a well-known technique to detect ^{240}Pu (12)). Passive gamma spectroscopy has been used to verify spent nuclear fuel content (11). Meanwhile, the laser-induced fluorescence (LIF) can provide information regarding the elemental composition by atomic excitation. The LIF has been used for actinides and lanthanides analysis in the nuclear fuel cycle (13). For this purpose, either a broadband laser or a scanning laser might be used. The information from the gamma and laser monitoring as well as thermocouples, neutron detectors etc. can be fed to the artificial intelligence (AI) to adjust fuel and molten salt concentration, laser power, etc. in order to assist real-time operation. The spectroscopic monitoring and feedback are part of the active safety. Some of the neutronic calculated transmutation processes of the present concept are demonstrated in Figure 3.

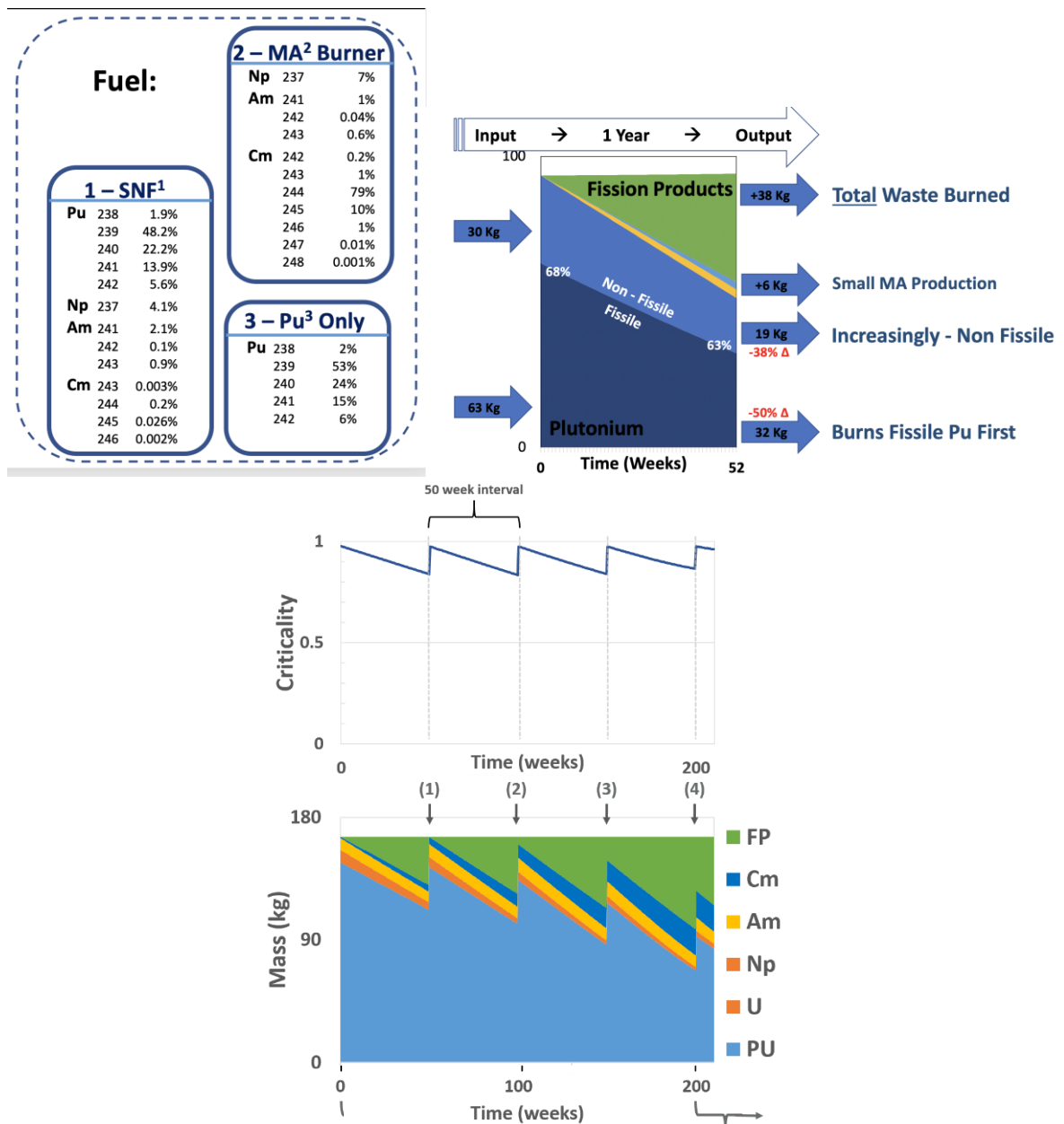


Fig. 3 A genetic Algorithm (GA) was introduced to handle the feedback capability demonstration on the hydrodynamical processes. An example of transmutation in molten salt solvent transuraniums with MeV neutrons with AI feedback control. (a) spent fuel examples; (b) burning of these by neutronics; (c) repeated updates of chemical and hydrodynamic processes, such as injection of the fuels as well as exhaust of fission products are carried out.

Passive safety features based on the molten salt are important design consideration for the transmutator (and also for a nuclear reactor). One example of passive density correction via a neutronic code is shown to illustrate this advantage (14). See Figure 4. The transmutator molten core in conjunction with a frozen plug on the bottom of the transmutator constitutes a system of a passive safety. The frozen plug may melt in an event of undesired core temperature increase and discharge the transmutator content into a tank containing neutron absorber, e.g. boron, and simultaneously freezing and encasing the content of the transmutator core thus mitigating dispersal of radiotoxic materials.

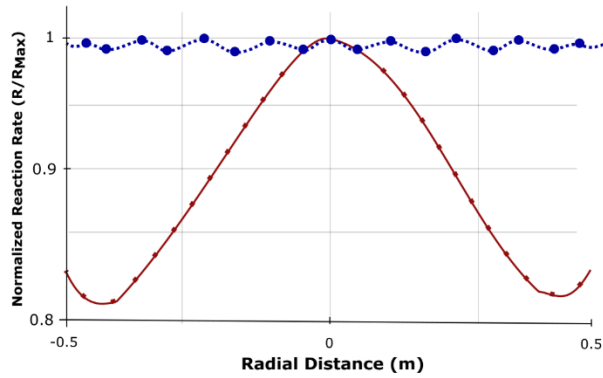


Fig. 4 Passive feedback controllability by the liquid nature of our transmutation. By our neutronic calculation we show the radial density generated may be self-corrected, if it goes higher than average, as the higher density spot is more reactive and thus heats up, which makes the liquid medium of this transmutator relax toward more uniform density. The relative reaction rate-based distance from center of example cylindrical core with reflective wall. Single source vs. multiple sources of neutrons also help further contribute toward passive safety feature of this concept. (Tanner 2020).

Another key safety and design feature is the operation near the atmospheric pressure. The molten core remains liquid at a high temperature of up to 1400 °C operating at low pressure (near 1 atmosphere compared to 100 atmospheres in a pressurized water reactor). Thus, in an event of a catastrophic rupture, explosion and dispersal become a lower probability.

A further feature of the liquid transmutator is the removal of the fission products (FP) and refuelling, while the transmutator is operating without requiring shutdown. The molten salt and TRU refuelling can be done jointly as a mixture or separately, whereas the TRU fuel may be injected as a pellet. The removal of FP depends on their chemistry. The noble gases (e.g., xenon, krypton) and noble metals fission products can be removed online *in-situ* by such a method as helium injection based on the law of partial pressures (15). The remainder molten salt composed of FP and actinides may be piped to the pyrochemical or the aqueous reprocessing performed off-line, whereas FP are removed and actinides and molten salt are piped back for further transmutation.

To extract energy from the molten salt, one of our suggestions is to pump a coolant (such as CO₂ or non-alkaline-liquid) through the transmutator core in place of pumping out the mixture of molten salt, TRU and FP into an external heat exchanger. This helps to minimize the presence molten salt and fuel in the external circuitry.

We see from the above that this transmutator serves as a provider of a backend to remove the most toxic portion of radioactive nuclear waste from a typical nuclear reactor by a thousand-fold, utilizing the three main vehicles of driving mechanisms:

- (i) Laser wakefield accelerated electrons (in the range of ~200MeV) are to be transmitted through thin low-Z filter into the molten salt;
- (ii) These electrons generate in the molten salt dissolving high-Z transuraniums, where electrons turn into gamma photons (in the range of many 10's MeV);
- (iii) These gamma photons in the molten salt generate neutrons (on the order of MeV) via photonuclear processes;
- (iv) These MeV neutrons have appropriately large cross-section to trigger the TU's transmutation. The combination of (i) - (iv) drives transmutation. (Earlier, some of fusion is driven by the beam-driven fusion process (Rostoker 2002)). In this realization, we see again that a substantial fraction of seed ideas has been sewn by earlier pioneers' efforts such as Veksler in 1956 from East and West coalesced (16).

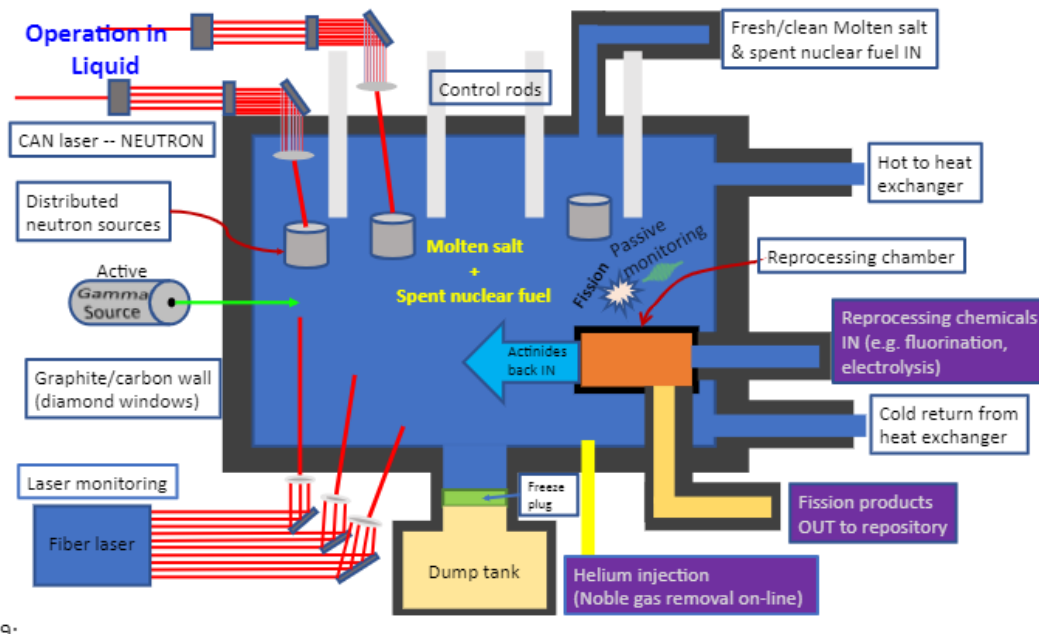


Fig. 5 Schematic operations in a sample case of transmutator. The liquid operation facilitates the ongoing operations of various levels in situ in the transmutation. We process the injection of the (unprocessed SNF on one hand, while we deplete transmuted disposables (mainly fission products. The local fluctuations of the density of fuels, for example, may be correctly by passive feedback feature of the molten salt. In addition, the transparency of the liquid allows a certain class of “visibility” by laser and other measurements. The cooling pipe system as well as the energy converter pipes are also inserted. The last system is discussed in the next section as to the carbon negativity. After Ref. (1)

4. Bio-inspired material for the wall

One of the characteristics of the nuclear energies such as fusion (or fission, or the above transmutator) is its highly concentrated power and associated intense radiation (or “temperature”, or “energy” as characterized by MeV, instead of eV or less for the fossil energy or other green energy). Thus, while we propitiate and control this high level of energy becomes available in nuclear approaches (fusion or fission at the level characterized by MeV), such high energy becomes a unique tool to treat and bring in additional capabilities such as the concentrated energy conversion route.

This means that on one hand, we have to have a first wall that can withstand severe physical and chemical conditions unlike any other than nuclear. On the other hand, we can take advantage of such high level of energy to harness its capabilities in a variety of forms, including chemical energy conversion in addition to heat and electric energy conversion.

There are no simple material that would meet all the requirements to shape the first wall of the Transmutator¹. This is why we propose to use nanotechnology to design a specific material made at the nanoscale. As said in (8), nature is a master chemist with an incredible talent. We need to master nanotechnologies in order to mimic nature’s techniques of giant trees pumping the water from the soil and bringing it at the highest level to the leaves without any electrical device or external source of energy as shown in figure 6. For the resilience of carbon-based materials chemically and physically, such materials are possible to be made in nanometric structures such as in carbon nanotubes, carbon fibers, etc. We use nanotubes and nanofibers, for example, to facilitate the first wall cooling and CO₂ conversion, etc. Nanomaterials inspired by the “artificial tree” concept contain such properties as their thinness to pass much of the hard radiations with

¹ T. Tajima , A. Necas : First wall for fusion reactor - intellectual property filed Aug. 11 - TAE 2017

only lower energy photons to capture, their ability to pump and circulate liquid (water) without external pumps, etc.

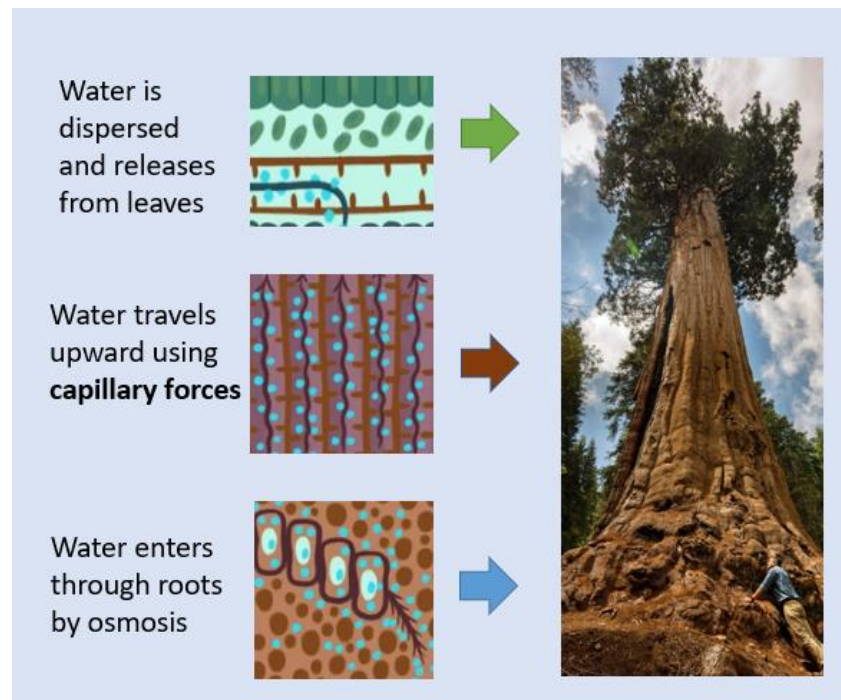


Fig. 6 Toward an “artificial tree” from the bio-inspiration of a sequoia tree.

If we limit our field to carbon materials, we have many candidates ranging from carbon nanotubes to graphene and nano carbon fibers. Each of these materials have extraordinary physical properties which can be imbedded in some complex system.

There are several known chemical paths of energy conversion in the chemical potential from CO₂, such as Haber and Sabatier processes from heat, or more direct photovoltaic processes. Because of the starting point of nuclear energy being at MeV with energies carried by neutrons, high energy gamma photons and X-rays, low energy photons (optical, infrared, and voltage separation), heat, etc., we have many more paths to navigate ourselves to convert the generated energy into chemical, electrical energies including the conversion of CO₂ via these paths. Perhaps, we can learn from trees that do so, so that we can realize “artificial tree” in the utilization of nuclear energy. This is a path we also learned to create “artificial intelligence” learning from our brains, via bio-inspiration.

4.1. Carbon-based materials

We discuss in particular the case of the first wall of a fusion reactor as a rendition of the “artificial tree” here. A tall sequoia tree can pump water (and other nutrients) high up through the trunk many 10s of meters. This is because the nanofibers and nanotubes of tree veins sustain the capillary effects of the surface tension that pull the water. Inspiration borrowed from a tree goes further. As mentioned in Table 1 below, carbon based materials are by far better in many aspects of physical and chemical damages by the severe conditions of nuclear reactor. Our “artificial tree” fibers may be made up of Carbon Nano Tubes (CNT). Carbon is hard to transmute by nuclear processes that can be severe on the first wall of fusion reactors or transmutators. The carbon-based nanomaterials have been also considered for novel accelerator applications (17).

4.2 Preliminary concept for the first wall of the Transmutator

The first wall will be in contact with the molten salt but due to the exterior cooling of the reactor a solidified layer of molten salt will be in contact with the first wall reducing the temperature at the interface. The first layer is just a protective coating between the molten salt and the constitutive carbon materials of the first wall. Among many possibilities we have selected three candidates because they can be easily used in thin layers and are able to sustain the corrosion of the molten salt: CVD diamond, glassy Carbon and CVD Silicon Carbide (SiC).

The next layer is the carbon-based material which is described below. Based on carbon nanotubes, graphene and graphitic carbon, the material gets its unique properties from the arrangement of the constituents. Figure 7 below shows the concept of the layered solution.

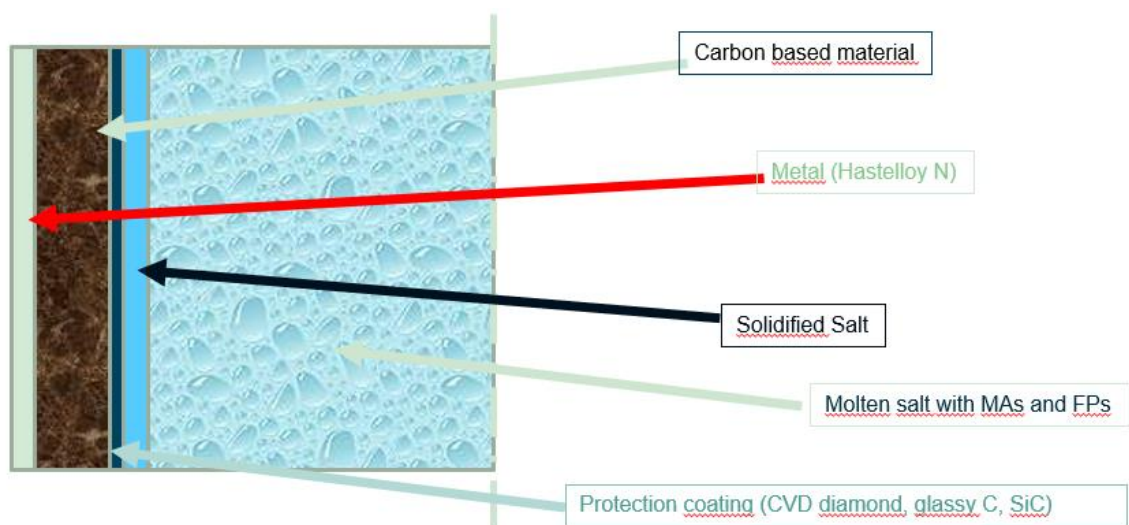


Fig. 7 Preliminary concept for the first wall of the Transmutator

Carbon nanotubes (CNT) have been discovered by Professor Sumio Iijima in 1991 (18), (19). Note that prior to such a discovery, Kubo (1958) (20) suggested nanoparticles. CNT are folded and wrapped graphene sheets in shape of tubes. There are two major types of CNT, the single wall (SWCNT) and the multiwall (MWCNT) exhibiting very different physical properties (21). They have extreme small physical size. Their diameter is around 1 nanometer where their length can go up to some millimetres with theoretical Young's modulus and tensile strength as high as 1 TPa and 200 GPa.

Carbon nanotubes have higher thermal and electric conductivities beyond the best metals. Their tensile strength is also stronger than metals, though they are easy to bend. Their thickness of the tube can be as thin as one Angstrom (single layer of benzene carbon layer, i.e. graphene layer).

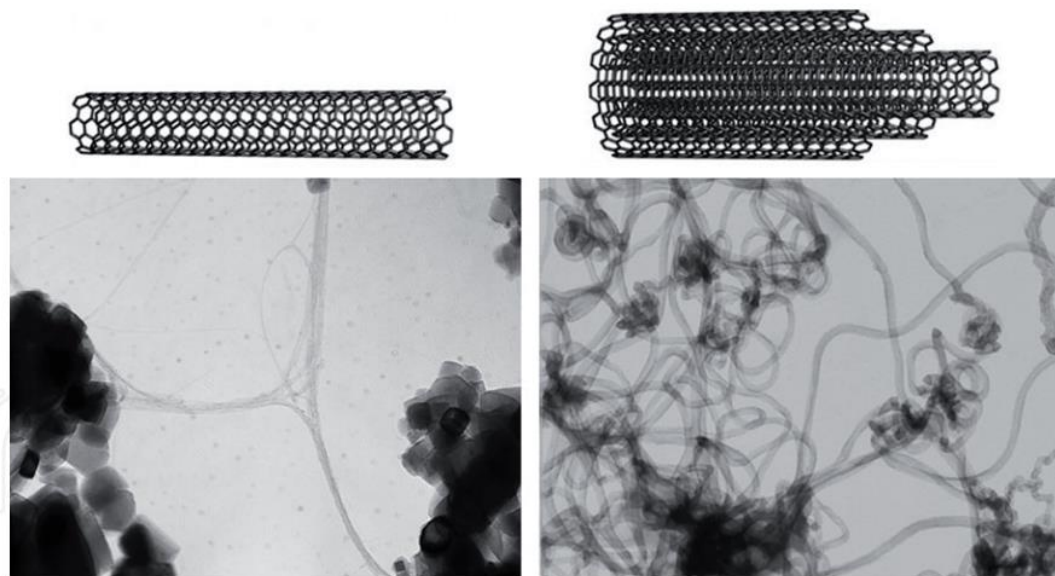


Fig. 8 Molecular representations of SWCNT (top left) and MWCNT (top right) with typical transmission electron micrographs below (22).

Many efforts have been made to aggregate nanotubes with conventional materials such as polymer or ceramic in order to benefit from their strength and conductivity at a practical scale. Depending on their hexagonal lattice arrangement and chiral vector, CNT could be ideal for nanocomposite structures. Many applications have been proposed for CNT, including conductive and high-strength composites; energy storage and energy conversion devices; sensors; field emission displays and radiation sources; hydrogen storage media and nanometer-sized semiconductor devices; probes and interconnects. Combining the extraordinary tensile strength with easy bending of CNT (or graphene), we could enhance the overall structural strength by combining these materials with framing struts that are harder to bend. Corrosion of the first wall by molten salt can be mitigated using graphene coating. High surface and deposition rate can be achieved using graphene dispersed in water. For example, Carbon Waters² masters the technology of these functionalized graphene layers for corrosion protection. In a similar manner, we also propose to use carbon nanotubes fabric and graphene layers for a fusion reactor first wall.

Carbon nanotubes are usually manufactured by the process of chemical vapor deposition (CVD). This involves heating a carbon source (usually methane or ethylene) in a chamber, and introducing the gas into a furnace which is kept at high temperatures (over 1000°C). The high temperatures cause the gas to break down and form tiny nanotubes, which are then collected. Other methods of manufacturing nanotubes include plasma-enhanced CVD and arc discharge. Carbon nanotubes are extraordinarily strong and light, meaning they can be woven into fabrics that are both durable and lightweight. Such fabrics are already being used in the aerospace and defense industries, and are also being explored for use in medical and consumer products.

It is possible to make an airtight nanotube membrane with carbon binder. Carbon nanotubes are strong and lightweight materials that can be used to create an airtight seal. Carbon binders are generally used to bind carbon nanotubes together and form a strong and flexible membrane. The combination of carbon nanotubes and carbon binder creates a highly durable and airtight membrane (23).

² private com. Alban Chesneau, Carbon Waters, Bordeaux, 2021.

4.3 Capillary design as part of the cooling of the fusion reactor

Energy producing reactors such as fusion reactor, fission reactors, and transmutators need to have a series of walls to confine the high energy and radiation producing central chamber(s). These walls, in part, can act as a cooling system of the reactor. Traditionally, walls are cooled through pipes with coolant circulated by a pumping system. This pumping system extracts heat and transports it outside of the central region. When the pumping system malfunctions (e.g., due to the lack of electricity), the heat removal stalls.

As Table 1 shows, the wall materials based on carbon can be better suited than those by metals. Beside these physical and chemical properties show in Table 1, heat and electrical conductivities of CNT and graphene can be superior to metals. To begin with, we have adopted the first wall to be ultrathin (and low-Z) so that the heat absorption is small, where the surface to volume ratio is large, and the wall material's heat conductivity of our choice is very large. In addition, CNT may act as a coolant conveyer through their very small capillaries. Capillarity effects inside a CNT material has been studied by several teams but none has proven that a flow of carbon dioxide CO₂ could be created through the wall by only capillarity process. The analogy of trees pumping the water from the soil to the leaves is invoked here. In order to create samples of wall materials, 3D nano-printing of CNT embedded into a nano porous media will be performed. The capillarity parameters of the samples will be measured then the samples will undergo series of test in molten salt and under high neutronic flux to insure their durability in service. The final architecture will be then design following the technical requirements of the reactor.

Nanotubes can be used to flow gases in a variety of ways. These include using them as a carrier for transporting gases, as a filter for cleaning gases, or as a membrane for gas separation. Nanotubes have also been used to create miniature gas turbines for powering small devices. Nanotubes have also been used to create gas sensors with increased sensitivity and accuracy. Finally, nanotubes can be used to store gases, such as hydrogen, for use in fuel cells. At this stage, we know that it is possible to drain CO₂ gas through carbon nanotubes using capillary pressure. This is done by creating a vacuum inside the nanotube, which causes the gas molecules to be drawn through the nanotube by the force of the capillary pressure. This process is known as capillary condensation and is already be used to separate CO₂ from other gases.

Accordingly, what is realized by the effects of our capillaries is an improved wall design to remove heat without the need of an external power source. This can be achieved due to the unique property of carbon nanotube. CNT have intrinsically high (or among the highest) heat (and electrical) conductivity and in addition are able to pump a fluid and bring it to a proper location for heat exchange and chemical synthesis purpose. If the tube diameter is so tiny that the surface tension of the fluid through the capillary effects can move the fluid, we save the pumping energy and structure for the fluid, a sort of self-regulating system of fluid circulation. In fact, this is what the Nature does so well (such as small plants to giant trees). We are bio-inspired here to make the fusion reactor not only carbon-neutral, but perhaps the fusion induced radiation can reduce the emersed CO₂ in the water liquid of the CNT tubes (24). Brian Wardle has shown that a CNT fabric can be used to infiltrate resin into a carbon fiber composite preform, without using device such as vacuum pump or infusion system. In this case the capillary pressure reaches 1 MPa (25). We need to study and develop a CNT fabric which is air-tightly woven. It may also provide a structural strength by forming a framework encircled by struts so that CNT fabric can pan out a tent-like area with the strength of the struts. The combination of such structured struts may compose a macroscopic size of the surface area of the wall. By engineering such subunits, the technology may become piece-wise structure and development. Another similar use of the capillary properties of CNT is the cooling of chips on an electronic board (26).

The capillary pressure inside a carbon nanotube is typically much lower than that of a traditional capillary. This is due to the small diameter of the nanotube, which reduces the surface tension of the liquid. The capillary pressure inside a nanotube is typically around 0.1 atmospheres. The following paper provides a comprehensive overview of the capillary pressure inside carbon nanotubes (27) and also (28).

4.4 Graphene as a substitute to Carbon Nanotube

Graphene is a two-dimensional material made of carbon atoms that are arranged in a hexagonal lattice. There are several methods for manufacturing graphene layers, including:

- **Chemical Vapor Deposition (CVD):** This method involves heating a carbon-containing gas, such as methane, to a high temperature and exposing it to a substrate, such as copper or nickel. The carbon atoms in the gas then deposit onto the substrate and form a layer of graphene.
- **Exfoliation:** This method involves using adhesive tape or a sticky substance, such as scotch tape, to lift layers of graphene from a bulk sample of graphite. The layers can then be transferred to a substrate for further use.
- **Epitaxial Growth:** This method involves growing a layer of graphene on a substrate, such as silicon carbide, using a high-temperature process called thermal decomposition.
- **Electrochemical Exfoliation:** This method involves using a strong oxidizing agent, such as potassium permanganate, to exfoliate layers of graphene from a bulk sample of graphite in an electrochemical cell.

No matter which method is used, the resulting graphene layers are typically very thin, with a thickness of just a few atoms. (29) It is possible to deposit graphene layers on a strut structure. One way to do this is by using the chemical vapor deposition (CVD) method, which involves heating a carbon-containing gas to a high temperature and exposing it to a substrate. The carbon atoms in the gas then deposit onto the substrate and form a layer of graphene. The substrate can be a flat surface, such as a piece of glass or a silicon wafer, or it can be a three-dimensional structure, such as a strut.

To deposit graphene on a strut structure using CVD, the strut must first be prepared by cleaning it thoroughly to remove any contaminants that might interfere with the graphene growth process. The strut can then be placed in a CVD chamber and heated to the desired temperature, at which point the carbon-containing gas is introduced. The carbon atoms in the gas will then deposit onto the surface of the strut and form a layer of graphene. It is also possible to deposit graphene layers on a strut structure using other methods, such as exfoliation or epitaxial growth. The choice of method will depend on the specific requirements of the application and the properties that are desired in the resulting graphene layer. (28) and (29)

Graphene can be made into an airtight membrane by using a method called lithography. This is a method of patterning an object by etching a pattern into a surface. The graphene is then etched into a pattern that is airtight and can be used as a membrane. (30)

4.5. From nanoscale to final scale

4.5.1 Using carbon nanotubes

The concept of the wall has to be designed and manufactured at nanoscale since to the best of our knowledge there is no macroscale manufacturing technique for this material.

Integration of CNTs in the form of fabrics or other preformed assemblies simplifies their handling and allows for the highest possible volume fraction of CNT content needed to better leverage

their properties in multifunctional (30), (31). The best way to handle CNT may be to have them in shape of long fibers in spool. In this formulation, a binder can be incorporated (32).

Additive manufacturing or 3D-printing have changed the way of manufacturing and designing ceramics parts. The strut structure also helps to match the additive manufacturing. It may also help to piece-wise and periodic replacements and updates, while the system as whole may not be disassembled. In this technology the 3D CAD model is digitalized in 2D slices that can be produced on top of each other. This enable the design of highly complex and precise structures which would not be possible to produce by classical method such as moulding and sintering, hot-pressing etc... There are different technologies depending of the feedstock form: slurry based, powder-based, or particulate with a bonder.

Additive manufacturing has gained significant attention in recent years due to its ability to rapidly produce complicated structures (33). In particular, nanoscale truss structures are becoming increasingly important in the design and fabrication of miniature devices, such as micro- and nanoelectromechanical systems (MEMS and NEMS). Graphite is a promising material for additive manufacturing of nanoscale truss structures due to its high strength-to-weight ratio, chemical stability, and low cost. Graphite can be selectively deposited using a variety of techniques, such as laser-induced forward transfer and focused ion beam deposition. These techniques can be used to create intricate 3D truss structures with nanometer-scale features. Furthermore, the use of graphite for additive manufacturing of nanoscale truss structures can be combined with other materials such as ceramics to create hybrid structures with unique properties.

The method considered here is to use 3D printing technology at nanoscale (34). A polymeric thermoplastic binder including the nanotubes will be printed on the carbon/carbon structural material. The extrusion technique will align the CNT in the required direction for the cooling flow [Figure 9]. Instead of a thermoplastic binder an alternative would be to use a monomer with photo-initiators additive. The light-activation polymerisation process will consolidate the part. After completion of the printing, the parts will be pyrolysis under inert atmosphere around 1100°C to remove the binder and form a porous and light Carbon Foam material including a dense array of nanotubes and/or graphene particles.



Fig. 9 3D printing of carbon-composite compound (court. of CMS)

4.5.2 Processing of continuous graphene layers

Continuous graphene layers can be obtained through several methods, including chemical vapor deposition (CVD), epitaxial growth, and chemical synthesis. The easiest method for producing continuous graphene layers is through CVD, which involves depositing carbon atoms onto a substrate using a hydrocarbon gas as a source. The substrate is typically a metal foil, such as copper or nickel, which provides a catalytic surface for the carbon atoms to form into a continuous layer of graphene. The CVD process is typically carried out at high temperatures (around 1000°C) and in the presence of a hydrogen gas to prevent the formation of amorphous carbon.

Another method for producing continuous graphene layers is through epitaxial growth, which involves growing graphene on a crystal surface that has a similar lattice structure to graphene. This method typically involves depositing a thin layer of metal onto a substrate, followed by annealing to create a clean, flat surface. The graphene is then grown on top of the metal layer through a process called chemical vapor deposition. Removing the metal substrate could be a problem for our application.

Finally, chemical synthesis can also be used to produce continuous graphene layers. This involves using a solution of graphene oxide, which is a highly oxidized form of graphene, and reducing it to produce graphene. The reduced graphene oxide can then be deposited onto a substrate to form a continuous layer.

The layer of graphene will be deposited as a final protection against corrosion. Eventually the final mechanical properties will be reached by a densification step using a CVD process.

4.5.3 The different Chemical Vapor Deposition processes for graphene

There are two main types of CVD processes used to produce graphene: thermal CVD and plasma-enhanced CVD (PECVD). In thermal CVD, the substrate is heated to a high temperature (typically around 1000°C) to facilitate the decomposition of the carbon-containing gas. In PECVD, a plasma is used to break down the gas molecules and generate reactive species that can deposit carbon on the substrate at lower temperatures (typically around 500°C).

One advantage of CVD for graphene production is that it can be easily scaled up to produce large-area graphene sheets. However, controlling the quality of the graphene layer produced by CVD can be challenging. Factors such as the temperature, pressure, gas flow rate, and substrate material can all affect the quality of the graphene layer, and optimizing these parameters is critical to achieving high-quality graphene.

In addition to CVD, there are other methods for producing graphene layers, such as mechanical exfoliation and chemical reduction of graphene oxide. Each method has its own advantages and disadvantages, and the choice of method will depend on the specific application and requirements of the graphene layer.

4.6. External protective coating for the air tightness made of SiC or its composites.

SiC Silicon carbide (SiC) is an extremely hard material commonly used in thin layers as an abrasive or as a coating to protect surfaces from wear. It is usually formed by chemical vapor deposition (CVD) or physical vapor deposition (PVD). SiC layers typically range from a few nanometers to several micrometers in thickness. The most common application of SiC is as a hard coating on cutting tools, such as end mills, drills, and saw blades. In this application, SiC provides superior wear resistance, heat resistance, and corrosion resistance compared to other materials.

Usually SiC layers are not airtight. While the material is very hard and provides superior wear and corrosion resistance, it is still porous and not able to form an airtight seal. To make an airtight

layer of SiC, one option is to use chemical vapor deposition (CVD) to deposit a coating of SiC on the substrate. CVD is a process that allows for precise control of the thickness and composition of the coating, and can be used to form an airtight seal. Additionally, the surface of the SiC layer can be treated with a sealant to further improve the seal.

The thick SiC membranes can be made using additive manufacturing. SiC can be used as a material in 3D printing, and some companies are developing 3D-printed SiC membranes for various applications. However, the process is still in development and has not yet been perfected, so it is not yet widely available commercially. Finally, the SiC membrane can be deposited on a truss structure. In fact, the process of chemical vapor deposition (CVD) is often used to deposit SiC membranes on truss structures, due to its ability to produce a thin and uniform layer with precise control over the thickness and composition. SiC membranes are often used in truss structures to provide additional strength and stiffness, as well as improved corrosion and wear resistance. SiC properties can be enhanced by fiber reinforcement such as SiC or Carbon fibers.

4.7. Further work

In a first step, tiles of the assembled materials will be manufactured to assess the feasibility at every stage of the manufacturing process. For example, we wish to study the chemical adsorption of protons to the first wall and its integrity under plasma. Qing-Xiang Pei and al. have predicted by MD simulation some effects highly dependent of the hydrogenation pattern (35) and (36). Some experimental data need to be generated in a similar manner as in (37). Bunch and al. have published an interesting result demonstrating that a monolayer graphene membrane is impermeable to standard gases including helium (38). Then a complete characterization campaign will check the chemical compatibility with molten salt, the behaviour under radiations (39) and the mechanical properties of the tiles (40). The capillarity pressure of the nano-tube network will be measured on separate samples as in (25).

5. Conclusions

The transmutation reactor using molten salt technology is capable of transforming large quantities of minor actinides from the spent fuel and thus able to solve the tough problem of long-term burial of nuclear wastes. The technology is at hand (30). We also consider the candidacy of the first wall of a fusion reactor that encounter severe high energy photons among other damaging radiations. The porosity and high heat conductivity of CNT can be a help to mitigate such radiation effects as well as the mitigate the so-called helium swelling problem of metallic crystals. We have shown that a technology for the first wall which is the critical part of the reactor can be proposed based on carbon materials under several physical kinds. The use of CNT as part of the first wall allows to create a cooling flow by capillarity in addition to its inherently high heat conductivity. It can be used also for the radiolysis of endogenic CO₂ and thus contribute to reduce the global warming. These are only the first step, from which we need to consider variety of issues. For example, for a fusion reactor case, the issues such as the vacuum hold, pressure hold and the chemical sustainability under the high flux of various photon passage, need to be studied and innovative schemes need to be suggested. Nanotechnologies holds promise of revolutionary changes for a wide range of applications in energy. Combined with bio-inspiration, they open a new era for the construction of safe, sustainable and efficient materials.

Statements and Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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