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FORUM 'USPEKHI-2021': CLIMATE CHANGE AND GLOBAL ENERGY ISSUES
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East meets West again in order to tackle the global energy crises

T Tajima, A Necas, T Massard, S Gales

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Contents

Abstract. The contemporary challenges of the impacts of human activities such as climate change induced by the increase in CO_2 emissions since the Industrial Revolution have been discussed throughout this Forum 'Uspekhi-2021', as have possible approaches to address these issues. Some have discussed nuclear approaches to remedy this situation, both fission-based and fusion-based. One of the challenges of the fission nuclear path is its radioactive spent nuclear waste, which can accumulate for a period longer than civilization has existed. If we recall, the first rapprochement between the East and West in 1955 was due to the desire to avoid nuclear confrontation between the East and West. East and West meet again, this time to find collaborative solutions to the global crises of climate change and other global environmental issues tightly related to worldwide energy issues. The meeting in 1955 launched the peaceful use of nuclear fusion energy, and since then we have witnessed, for example at this Forum 'Uspekhi-2021', the culmination of research in this area, like Norman Rostoker's aneutronic fusion approach driven by beam injection. At the previous meeting, Veksler also introduced collective acceleration using plasma to compactify accelerators. We are glad that we can show some of its fruits in the laser wakefield accelerator driving neutrons compactly and efficiently for the purpose of incinerating radioactive nuclear waste of transuraniums. These energy research efforts have also produced a path to follow in order to become carbon neutral or even carbon negative.

Keywords: carbon neutral energies, neutronic fusion, beam-driven fusion, collective acceleration, laser wakefield electrons, transmutation of transuraniums, carbon negative approach

T Tajima [1,a], **A Necas** [2], **T Massard** [3,b], **S Gales** [4,c]
[1] University of California at Irvine, Irvine, CA 92697 949-824-5011 USA
[2] TAE Technologies, Inc., Foothill Ranch, California, USA
[3] Stanford University, Stanford, California, USA
[4] IJCLab IN2P3/CNRS and University Paris-Saclay, France
E-mail: [a] ttajima@uci.edu, [b] massard.thierry@gmail.com, [c] gales@ipno.in2p3.fr

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1. Summary of the Forum

The world is now once again facing a huge and global crisis as great as or greater than the one we faced in 1955 of the emerging and serious nuclear confrontation of the two great powers of East and West. In 1955 scientists of East and West met at Geneva (International Conference on the Peaceful Uses of Atomic Energy, the 'Geneva Conference') to discuss this crisis and find approaches and cooperation between the two to seek some stabilization and future cooperation. We cite but two things close to us that happened at that meeting:

(1) the declassification of then classified research of nuclear fusion energy (which ushered in a new global international fusion research collaboration (leading to the creation of IAEA (International Atomic Energy Agency) among other things) [1];

(2) a suggestion to use plasma as a new collective accelerating medium beyond the conventional accelerators [2].

This time at focus is the issue of Nature's response to human activities, rather than the human confrontation between East and West, i.e., the human-created global issue of climate changes and related global energy issues. It is apt for us to consider, study, and act once again together in global scales on this issue, as our human impacts have become exponentially amplifying, so permeating, profound, and global. This time it is not only from East to West, but also

from Arctic to Antarctic, as we have seen and discussed in this Forum [3–6]. In 1955 East and West nuclear scientists gathered to tackle the former problem, while this year once again East and West scientists gathered to tackle the latter issue at the Uspekhi Forum on Climate Change and Global Energy Issues. This time some 65 years later, we might say that Mother Nature is getting unhappy and furious.

The overall presentations at our Uspekhi Forum (which was held on January 19, 2021) are stored in the webpage and one can review them here: https://uspekhiforum2021.org.

Since the Industrial Revolution, the human societies have learned and enjoyed the convenience and sweetness of the fossil energy. Further, since the quantum nuclear revolution of the 20th Century, the human societies have entered, been indulged in, and even doped by its power and convenience of the nuclear energy. Meanwhile, human societies have conveniently forgotten or postponed the treatment of the exhaust side of these powers ('toilet' or backend of the spent radioactive nuclear waste). On the one hand, the consumption of fossil fuel has dangerously accumulated CO_2 in our Earth environment. We have seen from many talks in this Forum that the climate changes have been incurred and accelerating.

2. The upstream side vs. downstream side of energy

This overall tendency is represented, for example, by the following fact: there are market place prices for various fuels (and energies derived by them, i.e., the upstream side), while there is no (so far) price attached to the ability and effort to remove CO_2 from the environment (the downstream side) (if the method of production of energy accompanies little or no production of CO_2, it may be hailed highly but not reflected by the market place prices). This incentivizes people to develop or dig up fuels (and to generate energy, upstream side (or 'kitchen science')), while there is little economic (if there is sociological or scientific) incentive to reduce or convert CO_2 (the downstream side, 'toilet science'). We point out here that a similar socioeconomic structure exists for the nuclear energy. If we produce energy by the method of nuclear energy, there is a price attached to it so that people can purchase and utilize it (upstream side). However, there is at this moment neither market place incentive nor societal dynamics to develop or process the waste arising from the nuclear energy production (such as high level spent nuclear waste, the downstream side).

Though the nuclear energy production is in principle (or directly, if not indirectly) insulated from the CO_2 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 latter 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 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 and the 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 are 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 [7]. 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 benefiting from Rostoker's aneutronic accelerator-driven fusion [8–10] (and fusion reactor-based neutron production [11]) as well as collective plasma accelerators that can help driven fusion neutrons effectively to incinerate radioactive nuclear wastes. We shall show some details of the latter here. We need not further enter this topic, as the paper [7] 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.

3. Path for transmutation of spent nuclear fuel and the method of neutron generation

We consider here an example of the demonstration of the downstream side of energy in the nuclear regime. This is the transmutation of spent nuclear fuel to incinerate the harmful and radioactive transuraniums and our suggested approach toward it.

3.1 Nuclear ladder for transuraniums

Anthropogenic impact is not limited only to the generation of greenhouse gases but also to the spent nuclear fuel (SNF), which is a by-product of fission nuclear power plants. The SNF is generated by two processes: (1) the fission or splitting of a fissile isotopes (e.g. $^{235}_{92}\mathrm{U}$), or (2) the radiative neutron capture which generates heavier nuclei. The fission process can be exemplified by

$$\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{139}_{56}\mathrm{Ba} + {}^{94}_{36}\mathrm{Kr} + 3\mathrm{n}\,,$$

with $^{139}_{56}\mathrm{Ba}$ and $^{94}_{36}\mathrm{Kr}$ as the fission products. The radiative neutron capture can be exemplified by

$$\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U} + \gamma\,,$$

leaving the heavier uranium isotope as a by-product by generating energetic gammas in the process. For a thermal neutron with energy 0.025 eV, the branching ratio is 85% for

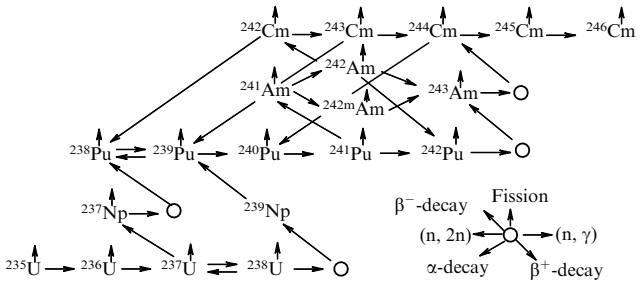

Figure 1. The depletion chain of actinides with the neutron interaction via the two main processes of neutron absorption and fission. This forms the nuclear ladders that go up with the neutron interactions and all products are transmuted and transformed.

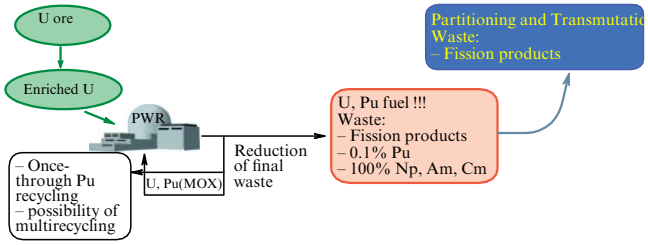

Figure 2. Nuclear fission reactors and the typical fuel cycles. The process of the partitioning and transmutation. PWR — pressurized water reactor, MOX — mixed oxide fuel.

fission vs. 15% for the radiative capture. The actinides depletion chain is very complex as illustrated in Fig. 1. Starting with $^{235}_{92}$U on bottom left, either a fission indicated by up arrow or a radiative capture, as shown by the right arrow, can occur. For each successive nucleus there is a competition between a fission, radiative capture and decay and a lower probability knock-on processes of (n, xn) with each process being subject to the energy-dependent cross section. The decay process has an associated half-life with for, example, $^{239}_{93}$Np having half-life of 2.4 days and $^{241}_{95}$Am having half-life of 432 years.

As a result of a nuclear power plant (NPP) operation a large inventory of SNF containing fission products and actinides exists. Altogether, there are more than 400,000 metric tons of SNF around the world with an active research addressing how to deal with it. The management of the fuel for the nuclear power plant from mining, refining, enriching, to utilization in NPP and reprocessing and storage is called the fuel cycle. There are two fuel cycles determined by the back-end reprocessing and storage: open fuel cycle, and closed fuel cycle. Open fuel cycle or the once-through process is not a cycle per se. Fuel is used only once, used fuel is then allowed to cool in the spent fuel pool for 10–20 years and then packaged and shipped into a storage. The closed fuel cycle is illustrated in Fig. 2.

The reason for partitioning and transmutation of the SNF is shown in Fig. 3. 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 (FPs) dominates the total radiotoxicity during the first 100 years. Long-term radiotoxicity is

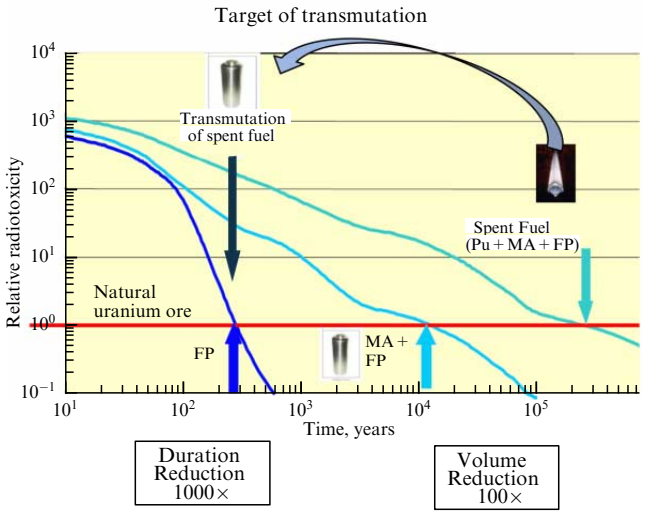

Figure 3. The radiotoxicity of various products of spent nuclear fuels produced from nuclear fission reactors. The two- to three orders of magnitude reduction of radiotoxicity. FP — fission products, MA — minor actinides.

dominated solely by actinides, mainly plutonium and americium isotopes.

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 transuranics (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 t^{-1} 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 t^{-1} U. Thereafter, Pu-239 is the main contributor to radiotoxicity with a value of 2×10^6 Sv t^{-1} U. Beyond 100,000 years, the total radiotoxicity decays to the level of 10^5 Sv t^{-1} 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 TRU 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.

3.2 Effective neutron production by laser wakefield accelerated electrons

The transuraniums by definition are all radioactive. In addition, as shown in Fig. 4, they tend to be more likely to get split through the fission process over the possible neutron absorption, if the energy of neutrons is greater than 1 MeV [12, 13]. There have been several suggested approaches, which include the accelerator-driven system (ADS) of transmutation [14–17] and fusion-driven transmutation [11]. One approach may be the spallation neutrons created by high energy beams [14]. The other approach is to utilize the fusion process (such as DT fusion) that produces MeV neutrons [11],

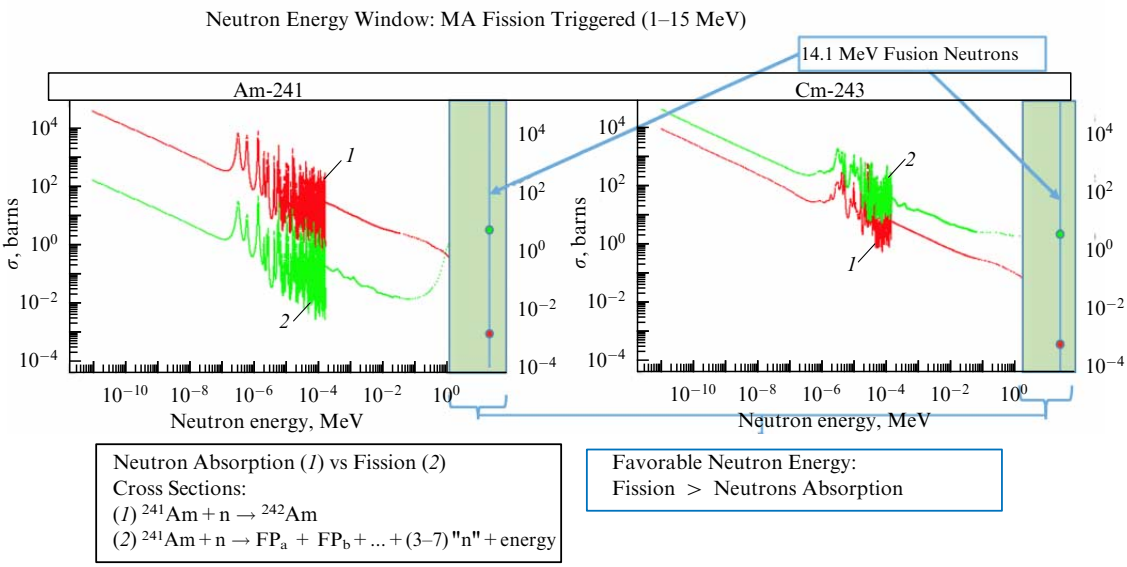

Figure 4. The fission cross section typically exceeds that of the neutron absorption cross section beyond MeV of neutrons for transuraniums. The advantage of MeV neutrons for transmutation [13].

The fusion may be triggered by the beam-driven fusion. In this case, the beam energies may be on the order of 100 KeV, while the DT-fusion driven neutrons are on the order of 10 MeV. This may make then eminent sense for us to drive transmutation processes of transuraniums by fusion-triggered neutrons, as the fusion neutrons are by birth in the MeV range of energy. Because of this behavior of energy dependence on neutrons as to transmutation, the approach to elevate energy of neutrons to the range of MeV makes sense. The deuteron ions may be accelerated by a small compact collective accelerator. We show a typical case for such an approach [13], in which the laser can drive coherent acceleration of ions by laser (CAIL) [13, 18]. The appropriate pulsed lasers that can drive such a process have been developed lately at various laser labs such as Extreme Light Infrastructure (ELI) labs [19, 20].

Here in the present paper a new approach is suggested, starting on the collective acceleration of electrons by laser, i.e., laser wakefield accelerated (LWFA) electron beams [21, 22] and their adoption to the transmutation. It has been demonstrated by a large array of experiments that pulsed laser can efficiently and compactly accelerate electrons [23–26]. More recently, the high density regime of laser wakefield acceleration pointed out the modest and high-efficiency acceleration of electrons that fits well for modest electron energies that introduce nuclear reactions of photonuclear processes [27]. We recognize that electrons in modest energies of 100's of MeV can induce efficient 10's MeV gamma photons in a high-Z material. These gamma photons, in turn, can create neutrons through the efficient photofission process in a few MeV range [28–30]. Figure 5 shows this concept. These neutrons (that are produced from LWFA and its derived gamma-triggered photonuclear process) are to drive transmutation of TRU dissolved in a molten salt to form a subcritical core. Even though the above processes of each step may be sequentially conducted, it is also possible to carry these steps in a whole in one. The suggested one-step approach of the above may be to irradiate laser-wakefield generated modest energy electron beam in the range of ~ 200 MeV (at the modestly high density regime) into the molten salt that

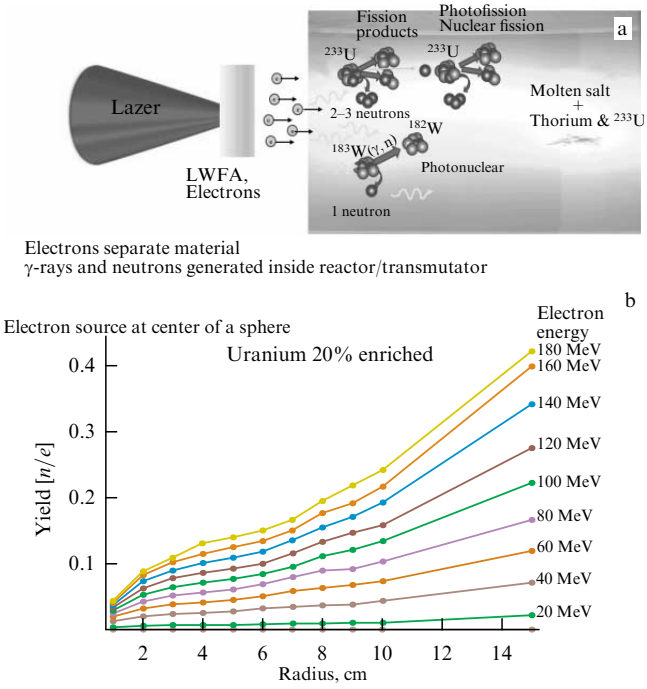

Figure 5. The gamma photon mediated transmutation: (a) Our suggested scheme. The wakefield acceleration drives electron beams through the high density regime of laser wakefield interaction on a target away from the liquid molten salt. These electron beams in turn drive gamma photons through high Z-matter interaction, which can be also in situ creating neutrons, which in turn transmute transuraniums. (b) Typical dependence of the neutron production yield (neutron to electron ratio) in photonuclear processes on the radius of a spherical U target for different energy of the incident electrons.

contains solvent transuraniums. Because of the very high Z-state of transuraniums and their high neutron content that is easily realisable by high-energy gamma photons (10–30 MeV), through the huge (γ, n) photofission cross sections in the region of the Giant Dipole Resonance, we may be able to have a convenient operational domain for nuclear transmutation of long-live TRU component of the SNF.

TRU elements are neutron-rich and radiotoxic. Neutron irradiation of TRU, which governs transmutation, has two major outcomes: fission or neutron capture (Fig. 4). Fission usually occurs for odd isotopes of actinides and is exemplified by $^{241}\mathrm{Am} + \mathrm{n} \rightarrow {}^{134}\mathrm{Cs}(2\,\mathrm{y}) + {}^{105}\mathrm{Ru}(36\,\mathrm{h}) + 2\mathrm{n} + 200$ MeV, and the neutron capture is exemplified by $^{241}\mathrm{Am}(433\,\mathrm{y}) + \mathrm{n} \rightarrow {}^{242}\mathrm{Am}(16\,\mathrm{h})$, where the time in parentheses represent half-life. The instantaneous neutron population within the transmutator is described by neutron losses (capture and escape) and neutron production (mainly from fission), yielding 3 operational scenarios for the transmutator: (1) supercritical: neutron production exceeds neutron loss, (2) critical: neutron production equals neutron loss (an example of this is the steady-state operation of a light water reactor), (3) subcritical: neutron loss exceeds neutron production. Neutrons originating from fission appear in two different time scales: (1) Prompt neutrons appear instantaneously following fission event; (2) Delayed neutrons appear after a time delay of milliseconds to minutes following fission event. It is the presence of the delayed neutrons that allows for the controlled critical operation of the LWR, i.e., their postponed appearance allows mechanical adjustments to maintain steady-state neutron flux and control. However, the fraction of delayed neutrons depends on the fuel isotope; fission of $^{235}\mathrm{U}$ or $^{239}\mathrm{Pu}$ produces 0.7% and 0.2% delayed neutrons respectively, with MA having delayed fractions $< 0.1\%$. Therefore, a critical reactor based on minor actinides as fuel suffers from decreased delayed neutrons, which makes it more difficult to maintain it stable. As a consequence, to incinerate large quantities of minor actinides, it is desired to introduce subcritical operation and externally injected neutrons to offset losses. Fission is a direct incineration of TRU. However, neutron capture can shorten half-life of long-lived actinide by creating an isotope with shorter half-life. We recognize that this method allows eventual incineration of all TRU, because the higher the atomic number ultimately becomes, the greater the susceptibility to spontaneous fission. We called this the TRU ladder climbing [31].

As already discussed in Fig. 4, we observe that the fission cross section dominates ($\sigma_{\mathrm{fission}} \gg \sigma_{\mathrm{capture}}$) for high neutron energies (> 1 MeV). Thus, in the transmutator the first neutron population (from the laser driven source) is unmoderated with energies of about 1 MeV; this is the reason why we cannot transmute actinides in a thermal reactor, where the neutron energy is thermal or epithermal. To facilitate the unmoderated neutron transport, we adopt the molten salt as the medium with a long history of research [32, 33]. Molten salt further helps the operation of our transmutator in several aspects, including safety, distributed nature, and change of parameters (such as the feedback possibility etc.). This combined with the reduced beam energy to induce neutrons, permits us greater flexibility in operation of the present concept. The neutron sources are compact and may be distributed within the transmutator molten salt core rather than a single neutron source. We have mentioned that each neutron source is driven by the efficient and distributed Coherent Amplification Network (CAN) fiber laser [34] consisting of bundle of fibers, thus each electron source may be miniscule and each neutron generation is in situ in the molten salt, as discussed above. Monitoring in realtime allows for a flexible and optimized operation. The coolant or suitable molten salt is piped into the core rather than piping the transmutator molten salt (and dissolved TRU and FP) to a heat exchanger.

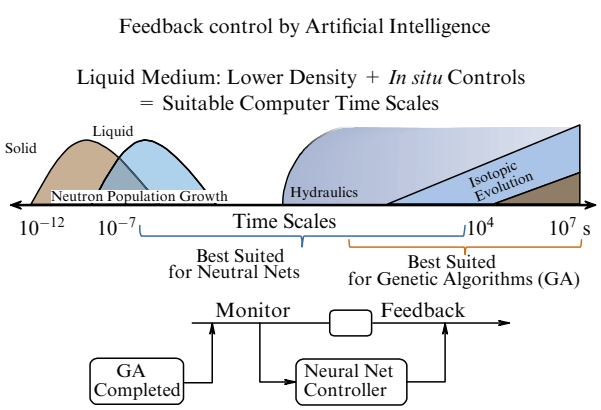

Figure 6. The opportunity for the feedback control in the liquid molten salt. The hierarchy of the time scales of the transmutator based on the liquid molten salt are not as disparate as in solid-operation for the purpose of feedback functions (nuclear type of interactions vs. hydrodynamic interactions).

3.3 Feedback controlled molten-salt transmutator

Our transmutator uses a liquid fuel composed of TRU dissolved in a suitable molten salt medium (e.g., mixture of lithium fluoride (LiF) and beryllium fluoride ($\mathrm{BeF_2}$)—FLiBe). The neutron generation method in the *in situ* molten salt with dissolved transuraniums 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 [31] via spectroscopy and consequent feedback control of the TRU refueling, reprocessing, and criticality further coupled with the monitoring of the distributed neutron sources (Fig. 6). 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 [35] to detect $^{240}\mathrm{Pu}$). Passive gamma spectroscopy has been used to verify spent nuclear fuel content [36]. 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 [37]. For this purpose, either a broad-band 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 [31]. 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 Fig. 7.

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

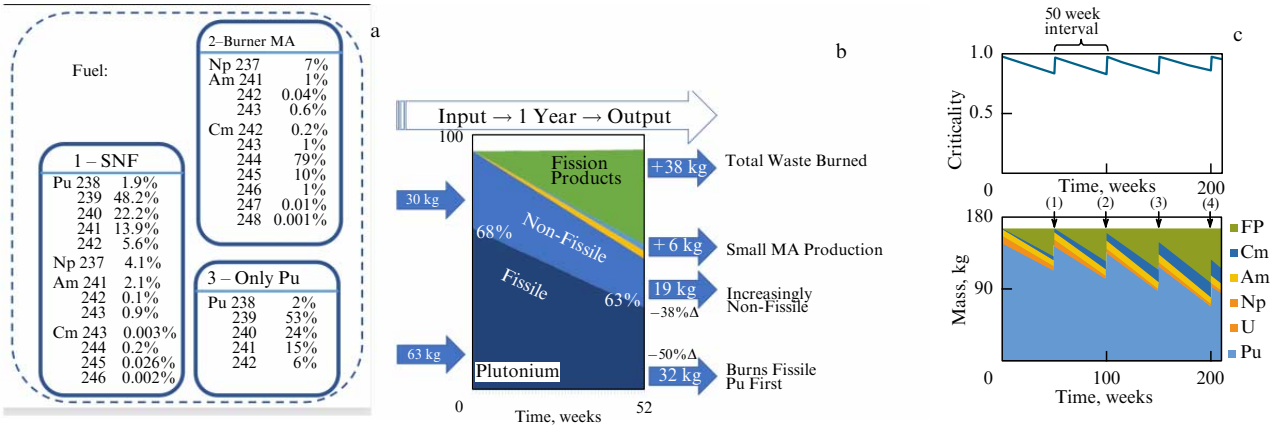

Figure 7. A genetic algorithm (GA) was introduced to handle the feedback capability demonstration on the hydrodynamical processes. An example of transmutation in molten salt solvent transuraniums with MeV neutrons with AI feedback control. (a) Spent fuel examples; (b) burning of these by neutronics; (c) repeated updates of chemical and hydrodynamic processes, such as injection of the fuels as well as exhaust of fission products are carried out.

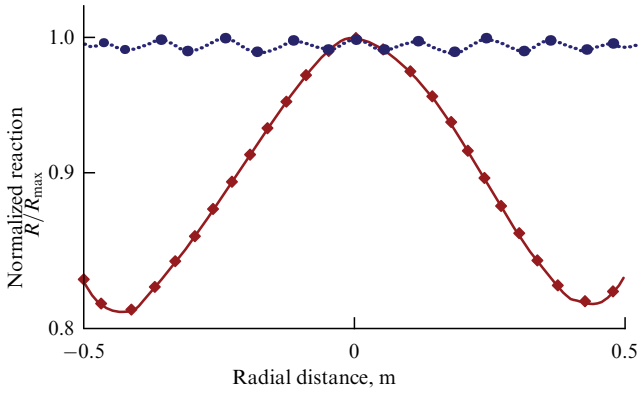

Figure 8. Passive feedback controllability by the liquid nature of our transmutation. By our neutronic calculation we show the radial density generated may be self-corrected, if it goes higher than average, as the higher density spot is more reactive and thus heats up, which makes the liquid medium of 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 [31].

correction via a neutronic code is shown to illustrate this advantage [31]) (Fig. 8). 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.

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 atm compared to 10^2 atm in pressurized water reactor). Thus in an event of a catastrophic rapture, explosion and dispersal become a lower probability.

A further feature of the liquid transmutator is the removal of the fission products (FP) and refueling, while the transmutator is operating without requiring shutdown. The molten salt and TRU refueling can be done jointly as a mixture or separately, whereas the TRU fuel may be injected as a pellet. The removal of FPs 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 [38] based on the law of partial pressures. 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 CO_2 or nonalkaline-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 of molten salt and fuel in the external circuitry. See Fig. 9 for our schematics.

We have introduced the rationales and a set of new operations and technologies that accompany the present approach. We note that there exist efforts in transmutation R&D based on possible burning of TRU in the Next generation of Fast Breeder Reactor [39], MOSART project [40, 41] or in the ADS (Accelerator Driven System) which consists of 100s MeV class proton superconducting linear accelerator (e.g., 600 MeV, 2–4 mA) coupled to subcritical core reactor loaded with TRU as fuel elements [14, 42]. Other approaches employ fusion-fission hybrid technology [43]. These efforts should increase valuable knowledge in critical areas.

We see from the above that this transmutator serves as the remover (or 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: (1) laser wakefield accelerated electrons (in the range of ~ 200 MeV) are to be transmitted through thin low-Z filter into the molten salt; (2) 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); (3) these gamma photons in the molten salt generate neutrons (on the order of MeV) via photonuclear processes; (4) these MeV neutrons have appropriately large cross-section to trigger the TRU's transmutation. The combination of (1–4) drives transmutation. (Earlier, some of fusion is driven by the beam-driven fusion process [42].) In

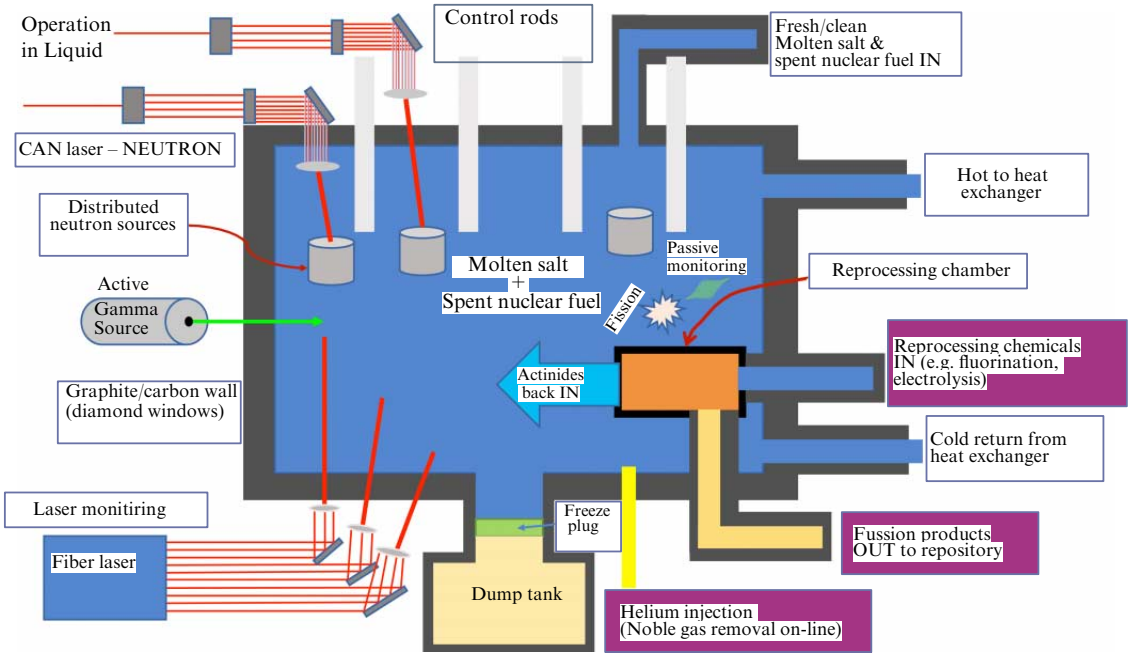

Figure 9. Schematic operations in a sample case of transmutator. The liquid operation facilitates the ongoing operations of various levels in situ in the transmutation. As indicated in Fig. 7, we process the injection of the (unprocessed SNF on one hand, while we deplete transmuted disposables (mainly fission products). As also shown in Fig. 8, the local fluctuations of the density of fuels, for example, may be corrected 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.

this realization, we see again that a substantial fraction of seed ideas has been sewn by earlier pioneers' efforts such as 1956 Veksler from East and West coalesced.

4. Carbon negative bio-inspired 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 becoming 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 the 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 several known chemical paths of energy conversion in the chemical potential from CO_2, 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 CO_2 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.

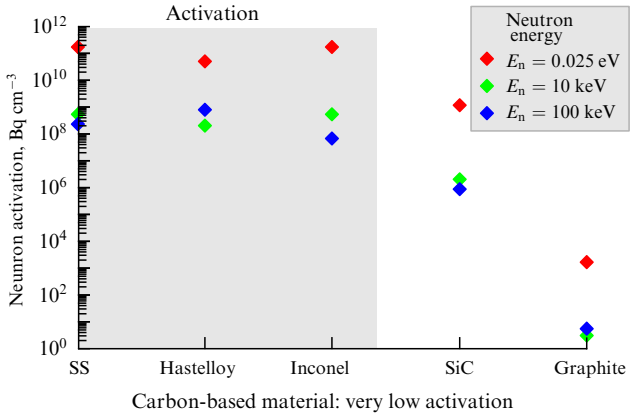

Figure 10. Radioactivation by neutron irradiation. Very low radio-activation for carbon-based materials compared with the conventional metals against neutron irradiation to ward wall materials. Such properties lead us to take carbon-based wall materials strategy.

In order to cope with the high energy (far beyond eV energy) in the nuclear reactors (fusion or otherwise), we need to take a strategy of 'divide and conquer'. That is, the first wall that faces all the highest energy radiations has to survive by the combination of the two factors: (1) to adopt the sturdiest materials against severe radiations (such as carbon, physically, for various conditions; see Fig. 10 and Table); (2) to make its thickness so tiny that nearly all radiations are permitted to transmit through the secondary walls, while on the other hand, to act to handle radiations which are either mitigated through the earlier walls and materials (in tanks etc.) or by still pass other parts of radiation passed through. This way each wall 'specializes' for particular radiation (or particular energy range) or particular purpose.

Table. Comparison of materials' physical and chemical properties in harsh radiative environment of reactors. We compare first three metallic candidates with the latter three carbon-based ones.

Materials	Neutron damage (dpa yr^{-1})	Neutron activation (Bq cm^{-3})	Corrosion	Physical properties
Stainless Streel 304	1	2.0124×10^{11}	53 μm yr^{-1}	Hardness = 140 kg mm^{-2} Melting point = 1400 °C
Inconel 601	0.9	5.2081×10^{10}	> 34 μm yr^{-1}	77 kg mm^{-2} 1400 °C
Hastelloy N	1.2	1.6824×10^{11}	8 μm yr^{-1} Corr. attacks Cr	50 kg mm^{-2} 1320 °C
Carbon composites	0.12 Maintained structural integrity up to 32 dpa	1.1959×10^{9}	Extremely low — nm yr^{-1}	2600 kg mm^{-2} 2700 °C
Graphite (reactor grade graphite)	0.0013	1.6358×10^{3}	No attack by salt 2.5 years of operation	Low < 40 kg mm^{-2} 3600 °C
Diamond	Very low (for detections) No data for wall, but should be even better	Only fast neutrons, in reaction $n + {}^{12}C \rightarrow \alpha + {}^{9}Be$	Extremely chemical inert	see diamond slide

dpa = displacement per atom.
Diamond: schemical stability, low neutron damage.
Graphite: many good properties.

In this philosophy, let us take the first wall case. In this, we make it by carbon-based nanometric walls. The choice based on carbon is sturdy due to its element's property (see Table). On the other hand, to make the thickness so thin, we achieve that most of radiations are passed through, perhaps only the lowest side of radiation such as infrared or optical level of photons are absorbed here. One of the secondary walls may also come in with a certain pass of energy of radiation, while the energy absorption may allow to make sufficiently high temperature or radiation wavelength to interact, we can make the particular absorptive radiation is converted into chemical energy stored from CO_2 molecules (and water or some other elements). If we insert such a circuitry in a tank where sufficient amount of energy (or heat), we can allow to extract the energy of some class of radiations into such energy as chemical by breaking up CO_2. In other words, we understand that along the multiple of radiation passage path from the center of reactor (starting from MeV) toward the outside (room temperature), we have a combination of radiative conditions, some of which can be acting in parallel.

We discuss in particular the case of the first wall of a fusion reactor as a rendition of the 'artificial tree' here. As we see in Fig. 11, 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 Fig. 10 and Table, carbon based materials are by far better in many aspects of physical and chemical damages by the severe conditions of nuclear reactors [45, 46]. Our 'artificial tree' fibers may be made up of Carbon Nanotubes (CNT) [47–52]. Carbon is hard to transmute by nuclear processes that can be severe on the first wall of fusion reactors or transmutators (Fig. 10). CNT has 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 Angstrom (single layer of benzene carbon layer, i.e., graphene layer [48, 49, 53–57]. 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 [58]. Carbon Waters in Bordeaux [59], for example, masters the technology of these functionalized graphene layers for corrosion protection.

This makes the most of radiation penetrating through these CNT fibers in the first wall, rendering another important feature that we let go 'unnecessary energy' in the first wall. Because of the thinness of the CNT layer and its tiny tube diameter the surface to volume ratio of the system of the bundle of CNT first wall is huge [60–63]. Such can serve to pass higher energy radiations to reduce the amount of stopped radiation. Porosity of some of the carbon materials also help in this. This reinforces one of our requirements on the first wall that we absorb least amount of energy and largest amount of spread of the absorbed energy (and heat) to avoid its meltdown. As mentioned, it has its own cooling system without the external pumping, as the capillary force pumps the liquid inside [64, 65]. Because of its thinness, low energy photons may penetrate directly inside of the CNT tubes, where direct photovoltaic energy conversion of CO_2 into other chemical compound, or heat-assisted chemical conversion of CO_2 [66–68]. Thus the first wall not only becomes the vacuum holding first wall function that it needs to satisfy, but also to function as an 'artificial tree' that can disperse the nuclear energy and convert some of its energy into chemical potentials (in addition to heat and electric energies). Unlike real tree fibers, our CNT fibers have extraordinary thermal (and electric) conductivity so that heat localization may be alleviated [69, 70].

Energy producing reactors such as fusion reactors [7], fission reactors [71], and as discussed in Section 2 — transmutators [13] 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.

Figure 11. Toward 'artificial tree' from the bio-inspiration of a sequoia tree. As shown in Fig. 10 for the resilience of carbon-based materials chemically and physically, such materials are possible to be made in nanometric structures such as carbon nanotubes, carbon fibers, etc. We use nanotubes and nanofibers, for example, to facilitate the first wall cooling and CO_2 conversion, etc. Nanomaterials inspired by the 'artificial tree' concept possess such properties as their thinness to pass much of the hard radiations with only lower energy photons to capture, their ability to pump and circulate liquid (water) without external pumps, etc.

When the pumping system malfunctions (e.g., due to the lack of electricity), the heat removal stalls. 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.

5. Meet the challenge and conclusions

We have started considering various innovative ideas and their realizations and challenges to make the downstream side of energy and its realization here. Once we focus our endeavor is this carbon negativity effort and its new paths to realize it, we can apply our method broadly to see its implications. As a crude but interesting check point for us is to apply our concept of the 'artificial tree' to the future reactors as well as perhaps existing fission reactors or even fossil reactors. We could take advantage of their heat (or energy) reservoirs from which we take their energy to convert CO_2 to make it carbon negative. Below we make such a tentative estimate.

We may be able to consider how some of the 'artificial tree' based on a typical fusion reactor (of future) or a fission reactor (of present) could be utilized to convert CO_2 via their heat and photons created by their reactions. If one unit of such a reactor is 100 MW electric producing unit, and if we assume that we take 10% of its energy out that otherwise would be dedicated to the electricity generation (or simply remain in the heat reservoir of the tank), a 100 MW power plant may be dedicating 10% of its heat or photon energies toward the above CO_2 conversion processes of 'artificial tree' functions. Then, we could convert CO_2 by utilizing 10^{12} J energy (10%) per day for this purpose. This would amount to 10^3 tons of CO_2. Such a number is only preliminary and implicative, but it might be interesting to see that E Musk presented his X-Prize for carbon removal to challenge approaches of carbon removal (1 ton per day of carbon removal as a scalable model entry) (Musk 2021).

The East and West again (since 1955) met this time looking jointly for the collaborative solutions for the global crises of climate change and other Earth environmental issues tightly related to the global energy issues. One of the lessons we are learning here is that our civilization should not only be interested in the upstream side (production) of energy but also pay attention to the backend side of energy. We are glad that some of its discussions and fruits of this Forum has spawn out the laser wakefield accelerator driving neutrons compactly and efficiently for the purpose of incinerating radioactive nuclear waste of transuraniums. In conclusion of this Forum, as the last talk (and the last review article reflecting all the Forum talks) as well as at the end of this paper, we can say that we have been inspired and deeply worried by and thanks to various observations and efforts to keep track of the climate changes that seem to be driven by the excessive CO_2 presence. Driven by such scientific evidence, several of the speakers presented some remedies to tackle these issues. We are humbled by these findings and the present review article is one of them. We also slightly generalized the CO_2 issues to those of the more global downstream side ('toilet') of energy. This includes the waste generation of spent nuclear fuel in the nuclear fission energy. Through looking at the heat reservoir (or the energy stored) in the current (or future) energy production devices, we can also take advantage of such a process as the path to make the carbon negativity, i.e., 'artificial tree'. We probably need all these efforts and we are still standing only at the very entrance to address the downstream side of energy issue.

Acknowledgments. The dawn of this paper was when one of the authors (TT) was given the duty to serve the French Atomic Energy Commission (CEA) High Commissioner (Professor Yves Brechet)'s Visiting Committee. One of his Visiting Committee gatherings was assigned to survey CEA's backend side of the nuclear energy. After we visited several large labs of CEA, TT was given an opportunity to personally see and chat with him. In this meeting we discussed how we could clean up the nuclear backend and I asked the following question: ''Do we have to carry out isotope separation for the radioactive nuclear spent fuel of transuraniums''? His answer was a surprise to TT and refreshing one: ''No, Toshi, as all the transuraniums are radioactive and eventually decaying so that isotope separation is not necessary''. Since then, our

ideas and research around them went by leaps and bounds. Here we thank Dr. Brechet's insight and prompt of us. In addition, it was Professor Gerard Mourou, who suggested TT to serve on the CEA Committee, also made the above epoch making meeting with Dr. Brechet after this Visiting Committee gathering was over.

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