

## Engineered-micro-hetro-structured self-separative fuel

**Liviu Popa-Simil**

LAVM LLC

Los Alamos, NM, United States

### Abstract

*The interaction between the fission products, their out springs and fuel structure determining its thermal stress and structural damage has an important role in limiting the burn-up factor.*

*By the 1950s fuel dispersion theory was created giving birth to the later cermet fuels. In fact by introducing a metal in the structure the thermal conductivity, expansion coefficient effects and radiation damage robustness have been improved, but the fuel cycle remained about the same.*

*A novel idea having its origins in the understanding of the complexity of the interaction between the fission products, nuclear recoils and lattice has been developed driving to a novel fuel structure called “cer-liq-mesh”. The new structure uses a liquid to take the fission products radiation damage and optimises the fuel beads dimensions.*

*This material combination has the advantage of eliminating simultaneously the fission products end or range damage and the thermal expansion cracks by moving the thermal spike power discharge of the fission products outside the bead. The ceramic beads are soaked into a liquid and stabilised mechanically by micro-metal wires bringing a several times increase in thermal conductivity and no fuel thermal stress at operating temperatures. The selection of the immersion liquid gives the buoyancy of the fission products making possible to have them float, as is the case for LBE or sink if NaK is used. The gasses have positive buoyancy and travel faster outside the liquid. The nuclear reactivity of the fuel is given by the fuel liquid ratio and may be adjusted by compaction. After a period of use of several years it is possible to recover the fuel by unsealing the pellets and mechanically extracting the fuel almost clean from the liquid that carries most of the fission products.*

*The easy fuel recovery and reuse reduces the need of hazardous chemical reprocessing procedures such as Urex, making possible for fission products to be easily collected and chemically stabilised and partitioned. These fission products might become a very special and precious ore of the future, if appropriately partitioned and stored. The “cer-liq-mesh” fuel in spite of its initial fabrication complexity is bringing significant improvements in usage and simplifications in waste treatment procedures.*

*The new fuel is almost equivalent with the actual LEU fuel and may have extended life in near constant reactivity adjusted by fissile-fertile isotopic ratios, being possible of being used in all the actual and future reactor structures from the PWR to travelling reactivity wave reactors.*

## Introduction

The actual fuel cycle mainly customised for PWR reactor usage has several major issues. Among the most important is the possible future “uranium peak” similar to the oil peak that may soon be declared officially. This is due to the fact that less than 0.5% of the processed uranium yellow cake is used to produce power, the rest being stored in the used fuel pools for years, to cool down for reprocessing [1].

Another very important issue results from the fact that PWR use enriched fuel, leaving behind large amounts of depleted uranium that can only be used in breeding processes. Breeding produces plutonium [2] that often encounters criticism based on the slippery grounds of proliferation.

Advanced nuclear energy is one extremely viable approach for achieving the required goals. With its extraordinarily high energy density (both per unit mass and per unit volume), it produces over seven orders of magnitude less waste than fossil fuels per unit of energy generated. The key is the use of advanced concepts, because conventional nuclear energy production suffers from depletion of fuel resources [3] even more quickly than fossil power [4]. Integrated breeding and full fuel usage are critical for future success potentially providing nuclear resources that will last for at least a millennium. Applying nano-technologies to nuclear reactors could potentially produce the extraordinary performance required.

On the other hand, climate change, globalisation of the market economy and demography urgently demand the development of nuclear energy. Nuclear energy is among the few alternatives that can survive and thrive under the threat of rapid change [5]. Energy solutions that are fully capable of meeting future needs for centuries to come in a reliable and affordable way are required. The key ingredient to any successful implementation is guaranteed abundant, inexpensive, clean energy. With sufficient energy, all other resources can always be obtained. Energy is also the central resource for cleaning and preserving the environment.

When the enrichment process is used, the mass of natural uranium needed rises up requiring a serious mining effort. Comparing this with the total planetary natural uranium resources of 35 Mt it is obvious that only 200 TWYears can be obtained implying a “nuclear fuel peak” in the next 70 years. The use of breeding can extend this to about 100 000 TWYear, making the nuclear power alone able to sustain the entire energy need of the planet for about 5 000 years, with no more mining required for the next 50 years. This is the difference that an intelligent use of fission products and breeding procedures involving plutonium can achieve at the planetary scale. This qualitative reasoning also shows that if the future energy will rely on nuclear power [6], plutonium-based breeding will become an essential element [7] for both a better self-sustaining fuel cycle with minimal nuclear waste and minimal negative ecological impact.

## Description of the actual work

The development of advanced nuclear applications based on micro/nano-hetero-structures requires intensive use of plutonium and other actinides to complement uranium and to improve performance.

The micro-nano-structured fuel has been developed to eliminate or drastically reduce the actual fuel limitations, including fuel cracking, fission product releases, radioactivity accumulation in fuel, low heat flow, low thermal conductivity, low operating temperatures leading to low efficiency, high waste volume, low burn-up factors and low fuel resources usage.

Previous studies [8] and experiments [9-11] have shown that it is possible to engineer micro-nano-structured fuel and achieve improved performance, and even reduce the need for high-hazard chemistry to reprocess the fuel and to partition and separate the fission and transmutation products.

From the theoretical point of view, the new micro-nano-structures can provide control requirements (in order to control a process, they have to be there at the right time, with the right configuration and dimensions, with appropriate sensing and reaction capabilities) applied to nuclear systems with emphasis on the “main actors” in the nuclear reaction that are the moving entities (particles and quanta), including neutrons, fission products, electrons, decay particles, recoils and neutrals (atoms, molecules, up to clusters).

The micro-nano-hetero-structure configuration is made of an assembly of three components and interfaces with generic functionality (generator, insulator, absorber) creating an elemental module specific to the moving entity that can be repeated as many times as necessary.

The “effective length” specific of each moving entity is used to set the correct dimensions of the elemental modules and to design the structure. This design is based on Monte Carlo Molecular Dynamics (MCMD) simulations. These elemental modules may be taken separately or together depending on the abundance of the moving entities and the desired treatment.

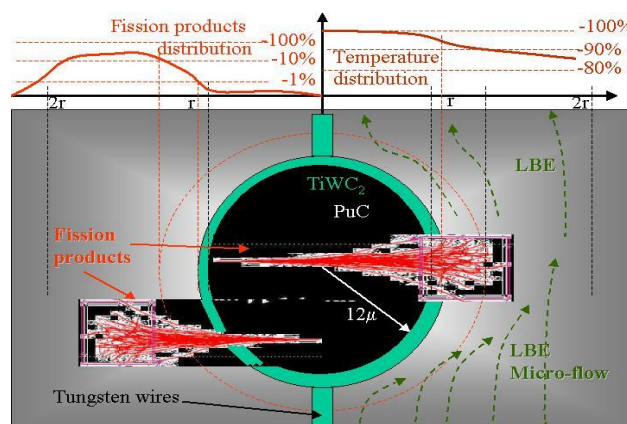
A specific development element is the design of the micro-hetero structured fuel “cer-liq-mesh” (ceramic-liquid-mesh fuel made of coated ceramic micro-beads set on a mesh deepen in a “drain” liquid, forming the micro-hetero structure of the fuel) is based on the fission product’s interactions with the fuel lattice, greatly diminishing radiation damage and maximising heat transfer, leading to more robust materials performance.

### The micro-hetero structure and its applications

The micro-hetero nuclear fuel is also called the “cer-liq-mesh” when it is made of a ceramic fuel structure stabilised on a refractory mesh structure and immersed in a liquid metal, to collect the fission products and smoothly drain them [12].

Figure 1 shows the cross-section of a single plutonium carbide (PuC) micro-bead, coated and immersed in a liquid such as lead-bismuth eutectic (LBE) acting as a drain liquid (DL).

**Figure 1: A coated plutonium fuel micro-bead immersed in a drain liquid, with the radial fission products and temperature distribution**

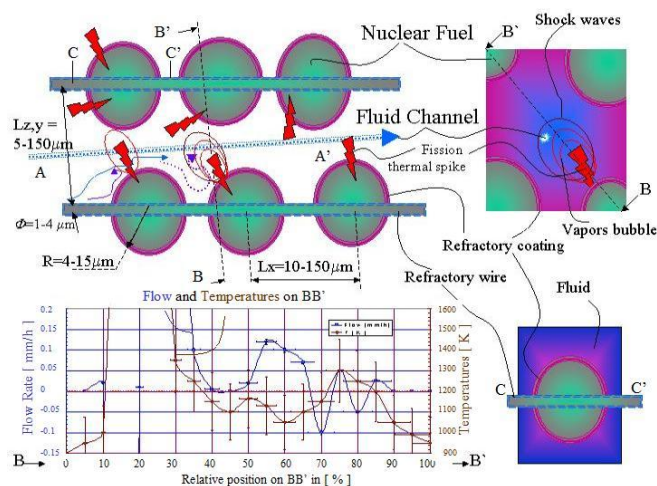


A particularly important scale is that of the range of the fission products resulting from the nuclear fission. This is due to the fact that these fission products carry the bulk of the energy of the fission reaction and furthermore, that most of the energy deposition per unit path-length and radiation damage are at the end of the range of the fission products [13]. The range of the fission fragments is dependent on their initial kinetic energy, their mass and charge, as well as the composition and density of the material through which the fragments are passing. Taking into account the average kinetic energy shared between the fragments (~170 MeV), and the average values of the other properties mentioned above, the range of the fission fragments is ~20-25  $\mu\text{m}$ . Thus the nuclear fuel micro-beads would have a diameter on the order of 20  $\mu\text{m}$  or

less and would have centre-to-centre separations of some  $50\text{ }\mu\text{m}$ . As such, the fission fragments would predominantly come to stop outside of the fuel micro-beads [14,15], in the liquid metal in which these beads would be suspended (currently proposed to be a lead-bismuth eutectic, although other liquid metals such as sodium/potassium could be used).

Figure 2 shows a lateral section view in a fluidic micro-channel made of adjacent micro-beads chains in the upper left. In the lower-left corner are the flow and temperature distributions along the median fluidic channel represented by the blue arrow and the BB' direction. In the lower right corner is a cross-section through the micro-bead similar to that in Figure 1, showing the coating and the refractory wire.

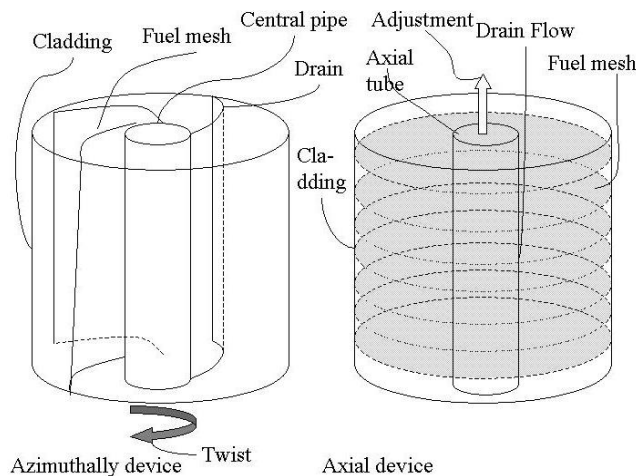
**Figure 2: Cross-section and details of a micro-fluidic channel made of four adjacent beads supported on mesh**



In the upper right corner is a cross-section through the micro-fluidic channel AA' in the BB' direction, showing fission energy deposition with its associated thermal spike. It should be noticed that the stopping process takes about 50 ps while the temperature equilibrium is established only after 100 ns or more.

Figure 3 shows an example of a compressible “cer-liq-mesh” fuel, similar to a pellet, but made of micro-beads supported on a micro-wire.

**Figure 3: “Cer-liq-mesh” fuel pellets**



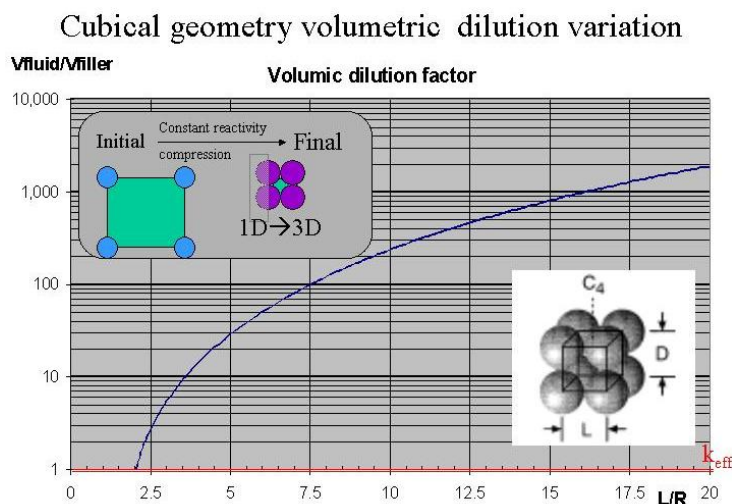
This has several immediate advantages:

- The most intense energy deposition and radiation damage would occur outside the ceramic fuel micro-beads (e.g.  $\text{UO}_2$ ), thereby minimising physical damage to them. The energy deposition would occur in the liquid where there is no physical structure to damage.
- The fission products, which together typically have a volume several times that of the starting solid fissionable fuel, would come to stop outside of the fuel micro-bead itself and hence, avoid major volume expansion inside the solid fuel beads, thereby minimising expansion induced cracking of the fuel beads.
- With the fission fragments coming to a stop in the liquid metal, the fragments could be gradually flushed outside the reactor core by a slow flow, preventing them from poisoning the reactor system by neutron absorption.
- The approach enables a far greater fractional burning of the nuclear fuel, thereby greatly reducing the radioactive waste.
- With the use of fuel micro-beads embedded in a liquid metal eutectic, there is less energy deposition in the fuel bead itself (which has a low thermal conductivity), a smaller thermal conduction path through the fuel before reaching the much higher thermal conductivity eutectic, and a much higher thermal conductivity on average for the reactor system as a whole. This reduces internal temperatures and thermal stress, allowing higher power density.

These structures are compatible with current PWR pellets, thereby giving them enhanced properties. Finally, we note that this fuel structure is capable of handling higher fuel enrichment, higher power densities, higher temperatures and higher energy conversion efficiencies.

Figure 4 demonstrates the capability of “cer-liq-mesh” fuels to vary DL volume in order to compensate for the loss of reactivity due to burn-up.

**Figure 4: The compression of the fuel structure**



Novel compact reactor designs for continuous fission product separation and ultra high burn-up include a variable shape nuclear reactor channel and the means to vary the fuel compression during burn-up.

The elimination of the fission products in short time after fission from the nuclear reactor's active zone provides important savings of the fuel and absorption rod mass, reducing the waste mass and its complexity.



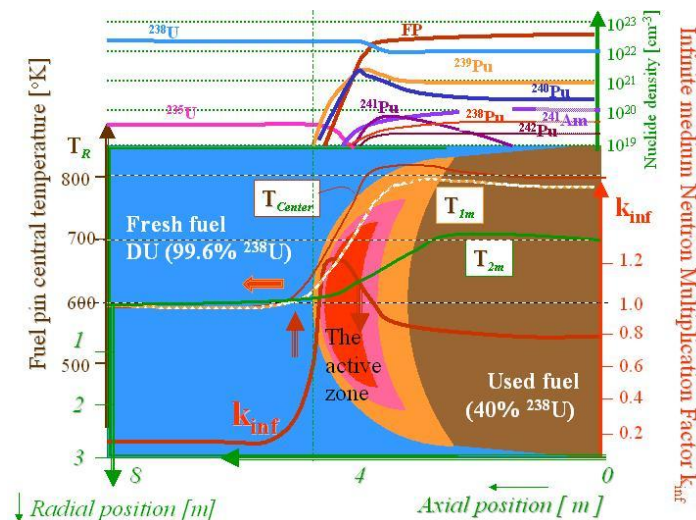
The actual removal of heat from the reactor core as a whole would still be handled by a secondary working fluid and not by the DL lead-bismuth eutectic. The eutectic would however do a much better job of moving the heat resulting from the fission reaction's thermal spike to the secondary working fluid. It also removes the poisoning effect of secondary transformation products and their decay products.

### CANDLE reactor type

CANDLE (Constant Axial Shape of Neutron Flux, Nuclide Densities and Power Shape During Life of Energy Producing Reactor) has many significant advantages related to its elimination of the need for enrichment and breeding. It is also a very proliferation-resistant nuclear power source [16].

Figure 5 shows a longitudinal section through a CANDLE reactor body, along with its main parameters variation. Because it uses DU, its dimensions are large (about 8-10 m long and 6-8 m radius). It burns from right to left, having the nuclear reaction initiation made with enriched uranium, and immediately after that it burns its DU fuel. In Figure 5, the reactor is at 50% of its life, with the active fission zone in the centre of the reactor.

Figure 5: The CANDLE or moving reactivity wave reactor



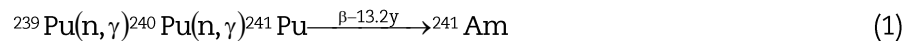
The lifetime of this system is over 30 years. It has an average burn speed of about  $\frac{1}{4}$  m/year, represented by the red horizontal arrow in centre. The abscissa shows the longitudinal dimension “axial position”, and the radial position is shown on the left lower vertical axis. On the left ordinate starting from the middle of the axes upwards is shown: the temperature at the centre of the fuel pin placed in centre of the reactor  $R = 0$ , the red curve “ $T_{\text{Centre}}$ ”; then at  $R = 1$  m, the brown-yellow curve; than at  $R = 2$  m, the green curve. It is seen that the temperature has a radial distribution following the shape of the neutron flux intensity shown by the central pattern, where the red area has the largest flux in the active zone. On the right ordinate is shown the criticality of the fuel “ $k_{\text{inf}}$ ” that becomes over-unity only near the centre of the active zone. In front of the active zone in the fresh fuel area, the reactivity is 0.2. After the burning zone, the reactivity is 0.8, being subcritical. On the chart above, sharing the abscissa with the reactor longitudinal section is shown the nuclide concentration as function of axial position at the centre of the reactor. This shows the basic mechanism that makes this structure operate like a nuclear reactor. The depleted uranium (DU) – the blue curve – is converted by neutron flux capture into  $^{239}\text{Pu}$  – the orange curve. Plutonium and  $^{235}\text{U}$  fission and they maintain the reaction in the active zone until the fission products (FP) – the brown curve – poisoning weight become sufficient to stop the breeding reaction, making  $k_{\text{inf}}$  subcritical. The waste fuel contains several per cent of  $^{239}\text{Pu}$  and sub-per cent amounts of minor actinides, as shown on the chart. After a few

decades the entire fuel is burned and the reaction stops, leaving behind a spent fuel containing about 40%  $^{238}\text{U}$ . This process uses about 60% of the extracted natural uranium, making the enrichment and breeding processes followed by Coex, Urex or Purex processes unnecessary. Of course, these processes must be applied to the spent fuel to extract uranium, plutonium and the minor actinides. It is important to notice that significant amounts of  $^{241}\text{Am}$ ,  $^{238}\text{Pu}$  and  $^{240}\text{Pu}$  may be obtained after the spent fuel reprocessing, partitioning and separation. This type of transmutation and burning reactor produces a high fuel economy and revolutionises fuel and waste management. It is also proliferation resistant. The initial delivery contains mainly depleted uranium, and after operation it contains an impressive amount of fission products, making chemical separation difficult.

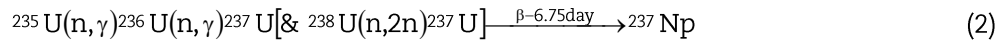
## Results and discussions

The micro-hetero-structure has the main advantage of remaining free of fission products that are drained out by the liquid, while the nano-clustered-structure has enhanced extraction of the transmutation products. Both processes based on the fluid drainage avoid the neutron absorption chain, preventing the formation of heavier isotopes. This process assures a simpler fission product map and higher-purity transmutation products.

Holding the  $^{239}\text{Pu}$  longer in the nuclear reactor enables increased fission, neutron absorption and transmutation [15], involving the reactions shown in Eq. (1) (which is also shown in part in Figure 3):



Having low-enriched uranium (LEU) fuel (0.1-0.5%) or residual  $^{235}\text{U}$  in the depleted uranium (DU) depending on separative work optimisation for that charge would increase neutron exposure and the probability of neutron absorption becomes important for the following reactions:

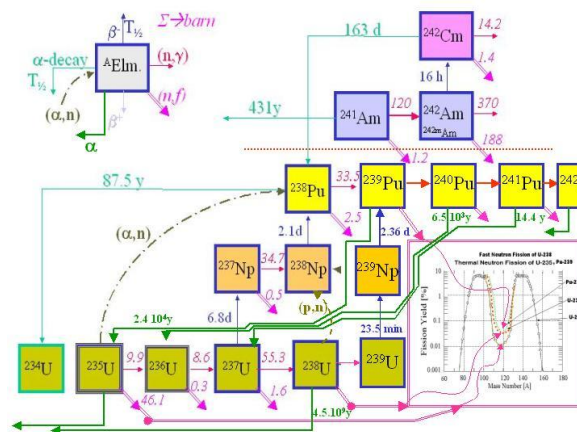


These reactions are minimised by the new nano-structure-based procedure in order to extract a super-grade plutonium or uranium.

Figure 6 shows the complexity of the nuclear process in actinides near  $^{239}\text{Pu}$ .

A nucleus-neutron interaction can involve scattering, with or without nuclear excitation or absorption that can induce fission or transmutation leading to a heavier isotope if followed by a multiple gamma or neutron emission or even a different element if a charged particle is emitted. The processes presented in Figure 6 are the main nuclear reactions used for fuel breeding with emphasis on alpha emitters as  $^{238}\text{Pu}$ ,  $^{241}\text{Pu}$ ,  $^{241}\text{Am}$  [17].

**Figure 6: Plutonium zone transmutation diagram**



The microstructure is used to enhance the separation of the newly created isotopes by transmutation, a process that leaves the structure with higher actinides that may be directly extracted at chemical fuel reprocessing.

The micro-hetero-structure deals with fission products that have a longer stopping range of about 14 microns in compact urania.

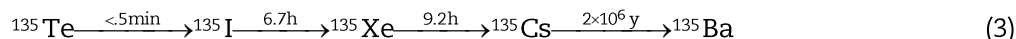
There are two main cases of operation of such a structure:

- The static case, in which the fluid is used to enhance the thermal conductivity and the radiation damage robustness, allowing diffusion of the fission products inside following a Brownian path under the influence of buoyancy.
- The dynamic case, in which the fluid, driven by a pressure gradient, slowly moves through the microstructure, removing the heat produced by the fission products.

In both these cases the pellet is sealed and the fission products do not escape to produce contamination.

The dynamic case involves a continuous circulation of the drain liquid with a speed sufficiently small to avoid hydrodynamic stresses on the fuel beads, but large enough to optimally remove the fission products from the hot zone.

This system removes the first group of fission products ( $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$ ,  $^{151}\text{Sm}$ ) and the second group ( $^{79}\text{Se}$ ,  $^{126}\text{Sn}$ ,  $^{93}\text{Zr}$ ,  $^{99}\text{Tc}$ ,  $^{135}\text{Cs}$ ,  $^{107}\text{Pd}$ ,  $^{129}\text{I}$ ), avoiding the undesirable consequences of subsequent neutron absorption.

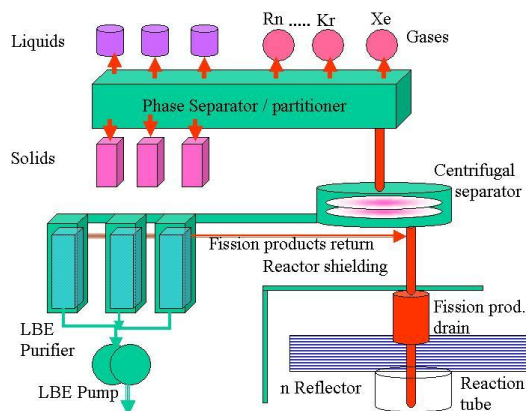


It is known that the yield of  $^{135}\text{Te}$  is of about 8% and the cross-section of  $^{135}\text{I}$  is a factor of 10 000 greater than that of  $^{239}\text{Pu}$ , as shown in the lower right of Figure 6. This simply means that no Pu in a volume of  $10 \text{ nm}^3$  around will be burned until the  $^{135}\text{Xe}$  is transmuted into  $^{136}\text{Xe}$  which has a lower neutron absorption cross-section.

The micro-hetero-structure moves the  $^{135}\text{I}$  out of the neutron flux and concentrates it in the narrow central drain tube. Only at very high flow rates is the production of  $^{136}\text{I}$  minimised. Otherwise it remains in reactor hot zone, but is not shielding the fissile material, in a similar manner to the rim effect being stabilised in drain liquid by a molecular bound.  $^{135}\text{I}$  can prevent neutron absorption in nearby liquids or structural materials, at a cost of about 3% of the neutron excess.

The fission products released into the drain liquid can accumulate on the pellet walls, leading to easy cryogenic separation in the static-fluid encapsulated pellet case. The fission products can also be driven outside the reactor hot zone where they can be separated on-line as shown in Figure 7.

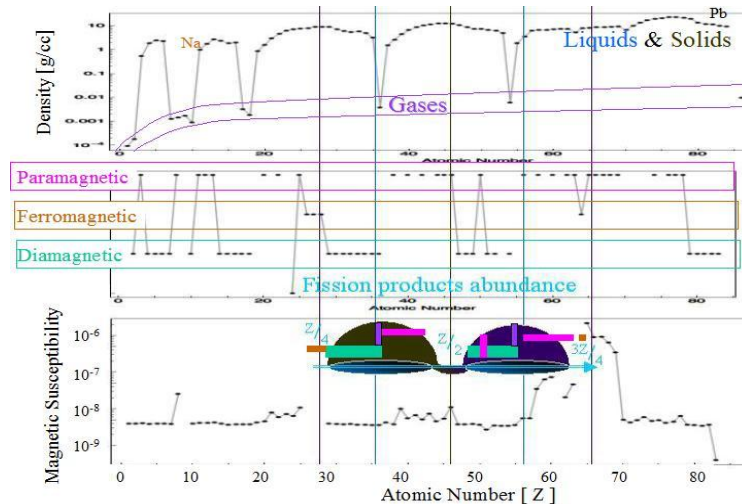
**Figure 7: The on-line microchemistry fission product separation system**





The separation process can utilise either centrifugal force exploiting buoyancy or electromagnetic forces to exploit the differences in charge-to-mass ratios as shown in Figure 8.

**Figure 8: Fission products magnetic properties**



The upper chart shows the density variation with the element number. The lighter elements are gasses, but at atomic level this property will not manifest directly, except for noble gases that do not interact or dissolve in the drain liquid. For example, until becoming Xe, the buoyancy properties of  $^{135}\text{I}$  cannot be utilised because of the drain liquid atom/iodine combination that determines the effective buoyancy.

The middle chart in Figure 8 shows the magnetic properties as ferro-, para- and diamagnetic, and the lower chart shows the nuclear magnetic dipole moment. The coloured domes show the fission product density of occurrence distribution, similar to the chart in Figure 6, but in an axonometric view to indicate the in-depth distribution due to n-induced transmutation appears behind the atomic number increasing the complexity of the process.

The micro-hetero structures are novel concepts in reactor fuel management providing continuous separation and extraction of the fission products considered “poisons.” Related dedicated structures can be incorporated into nuclear reactor design, meant to specifically deal with a class of materials, finding similarities with the biology and living beings.

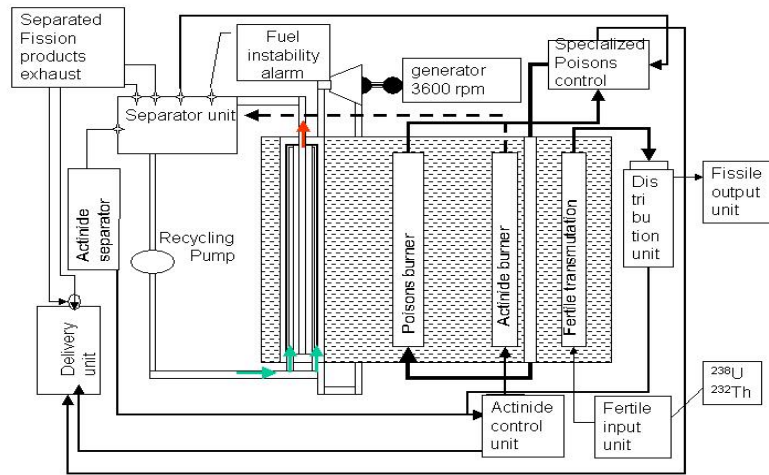
Figure 9 presents a schematic for a nuclear reactor based on dedicated functionalities of the reactor zones. The central zone is dedicated to fission surrounded by dedicated reaction tubes and associated microchemistry devices for burning “poisons” and actinides, and transmutation and fuel breeding. The complexity of these processes is much greater because each process including fuel breeding and fuel and minor actinide burning may encounter many fission products. Accelerators and spallation processes can be used to control the neutron balance.

### CANDLE reactor enhanced fuel structures

The advantages of the progressive wave reactor shown in Figure 5 can be enhanced by using micro-hetero-structures to produce a CANDLE advanced reactor design, similar from the neutronic and fuel handling point of view to pebble bed reactor [18] (because the fuel is moving in order to maintain a steady state in the active zone).

The main purpose of creating a burning wave is to increase fuel burn-up, in order to improve the natural fuel utilisation factor and to minimise the need for enrichment [19].

The burn-up is a measure of the fraction of consumed nuclear fuel in atom % and a measure of the extracted specific energy in MWd/kg. Burn-up of 1 atom % produces about 10 MWd/kg.

**Figure 9: Novel nuclear reactor fuel management**

In order to clearly show<sup>1</sup> the potential advantages of extracting the fission products out of the reactor's active zone and directly separating them by the microchemistry units, a single-group diffusion equation was used [with reference to Figure 9 "FP" (fission products) curve] that can be written as:

$$\frac{d}{dl} \left( D \frac{d}{dl} \phi \right) + v \Sigma_f \phi - \Sigma_a \phi = 0 \quad (4)$$

Here,  $l$  is the axial position in the reactor;  $D$  is the diffusion coefficient;  $v$  is the average number of generated neutrons per fission;  $\Sigma$  is the macroscopic section for fission ( $f$ ) or absorption and transmutation ( $a$ ); and  $\phi$  is the neutron flux.

The neutron flux will approach zero at the borders of the reactor where  $l = 0$  or  $l = l_{max}$ .

For a simplified [ignoring radioactive decay and (n,2n) reactions] transmutation chain of  $n$  elements, the burn-up equations are:

$$\frac{\partial N_i}{\partial t} = -N_i \sigma_{a,i} \phi + N_{i-1} \sigma_{c,i-1} \phi \quad i = m:n \quad (5)$$

and for fission products:

$$\frac{\partial N_{FP}}{\partial t} = \sum_{i=m}^n N_i \sigma_{f,i} \phi - \eta N_{FP} \sigma_{a,FP} \phi \quad (6)$$

Here,  $N_i$  is the atom number density of element  $i$ ;  $\sigma_{a,i}$ ,  $\sigma_{f,i}$  and  $\sigma_{c,i}$  are the microscopic absorption, fission and capture cross-sections of isotope  $i$ ; and  $FP$  is the fission product pair and  $\eta$  is the fission product removal efficiency. The macroscopic cross-sections are:

$$\Sigma_a = N^i \sigma_{a,i} \quad (7)$$

$$\Sigma_{tr} = N^i \sigma_{tr,i} \quad (8)$$

$$v \Sigma_f = N^i v_i \sigma_{f,i} \quad (9)$$

1. This calculation was made only to show the effects of removing fission products from the active zone of the reactor and their qualitative potential consequences. The theoretical model is identical to Ref. [18], except a parameter called "fission product removal efficiency" introduced in Eq. (6).

$$D = \frac{1}{3\Sigma_{tr}} \quad (10)$$

Here,  $\Sigma_a$  and  $\Sigma_f$  are the macroscopic absorption and fission cross-sections and  $\Sigma_{tr}$  is the macroscopic transport cross-section. The burn-up depends on the neutron fluence:

$$\psi = \int_0^t \phi dt \quad (11)$$

and:

$$l = l_0 + vt \quad (12)$$

So,  $\psi$  can also be written as:

$$\psi = \frac{1}{v} \int_0^t \phi dl \quad (13)$$

where  $v$  is the displacement speed.

The diffusion equation becomes:

$$\frac{d}{dl} \left( D \frac{d}{dl} \phi \right) + [k_\infty - 1] \Sigma_a(\psi) \phi = 0 \quad (14)$$

The solution can be a solitary burning wave, with an active zone displacement speed,  $v$ . The classical solution has a speed in the range of few cm/year and a power density up to 200 MW/m<sup>3</sup>.

The effect of the fission-product-removal efficiency,  $\eta$ , in Eq. (6) is similar to a reduction of the fission product absorption cross-section from about 35 barn to obtain the  $FP_s$  curve in Figures 10 and 5 to about 4 barns for the  $FP_{drain}$  curve in Figure 10. This reduction increases the active zone displacement speed, increases the burn-up factor, and increases the local active zone reactivity.

The corresponding neutron excess can produce higher power densities and improved mixtures of DU-Th and other transmuted isotopes.

The elastic micro-structure together with a dedicated reaction channel and the use of nano-clustered structures can produce an optimal functionality. One can burn natural uranium mixed with thorium or depleted uranium. One can also concurrently produce by transmutation commercially valuable isotopes needed for power, industrial and medical applications.

In Figure 10, two versions of nuclear reactor are shown that use variable-geometry micro-hetero-structured fuel in combination with nano-clustered transmutation fuel as the reflector and blanket. Also shown are the longitudinal concentrations of various heavy metals and fission products.

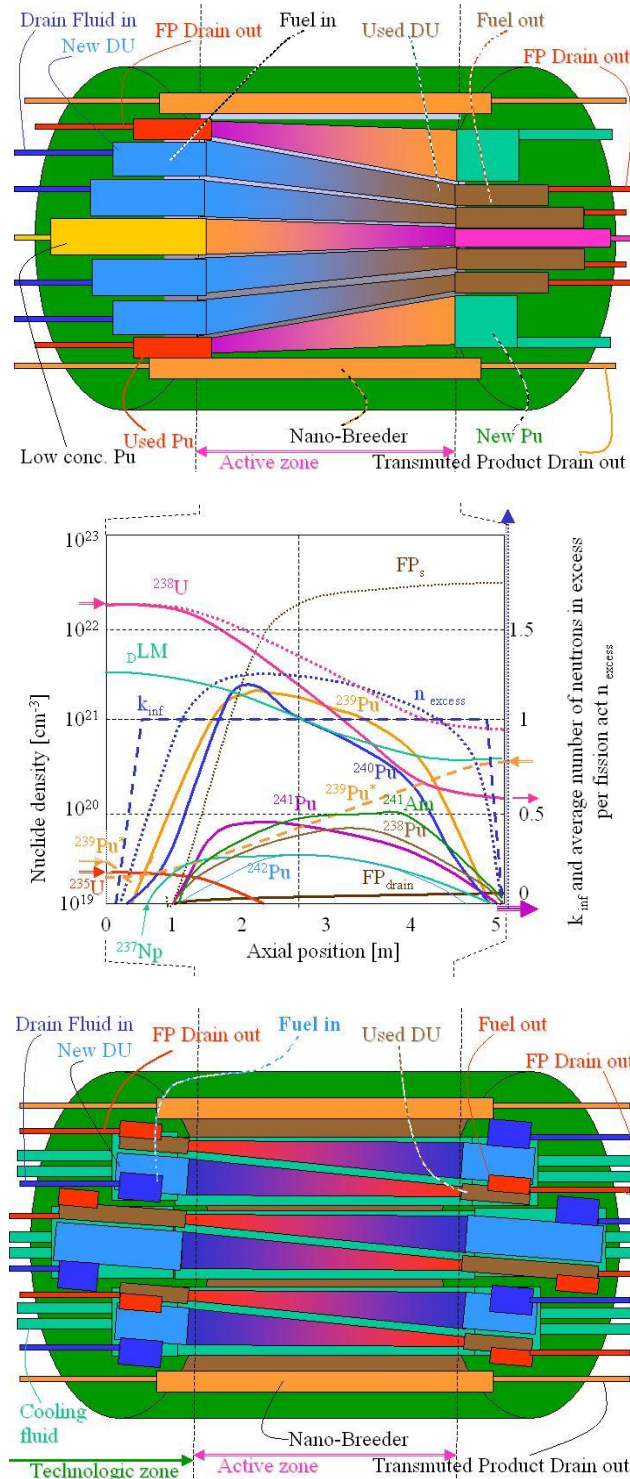
The reactor schematic diagram shown in Figure 10(a) above uses a bi-directional conic-shaped fuel tube geometry.

On exterior is fed with plutonium-based micro-hetero-structure with the role to assure the uniform inside neutron flux and excess of reactivity to assure a deep burn-up of the inner DU fuel.

The fresh micro-structured DU with a <sup>235</sup>U content as low as 0.2% is fed into the reactor through the ports. By using the micro-structured <sup>239</sup>PuC, a constant neutron flux is maintained throughout the reactor zone. This zone coincides with the active zone of the solitary reactivity wave in Figure 5. The Pu fuel concentration and a compression adjustment is made in order to perform a near perfect burn-up of the DU fuel. The centre plot in Figure 10(b) shows the evolution of the nuclide densities in the DU fuel. At the entry point, the fuel is mostly uranium. Its concentration decreases as the fuel advances. The decrease in uranium is compensated by

**Figure 10: Schematic diagram of CANDLE burn micro-hetero-structured fuel reactors**

- (a) Conic shaped reactor tube for DU-Th fuelled, aided by Pu (top)
- (b) Chart showing the longitudinal dependence of isotope concentration in DU channel of Figure 10(a) with fuel travelling from left to right (middle)
- (c) Bi-directional fuel loading reactor using DU-Th only, with transmutation capability (bottom)



the increase in plutonium isotopes and in the fission products (FP<sub>s</sub>) that at the end dominate the nuclide density for the CANDLE or pebble bed reactors. For the micro-structured fuel, the drain fluid eliminates the fission products, as shown in the FP<sub>drain</sub> curve, leaving an excess of reactivity of up to 10%.

The plutonium family appears through transmutation, and then disappears as a result of the advanced burn-up with the surplus of reactivity sustained by the plutonium fuel.

In Figure 10(c) another case of DU reactor mainly is shown with the fuel travelling in both directions. The charts in Figure 10(b) are only valid for the fuel travelling from left to right. For the fuel moving in the opposite direction, the chart axial axes have to be reversed.

This type of reactor has to have large dimensions. These dimensions are needed to assure criticality and a good neutron economy. Both are achieved by reducing the lateral surface leakage factor. Using a reflector and a transmutation absorber further minimises this leakage.

A CANDLE burn-type micro-hetero-structure with continuous fission product removal produces a low-enriched uranium product that offers a near perfect burning and simplified fuel reprocessing. It is better than the OTTO cycle because almost all the actinides are consumed.

The “added complexities” of the micro- and nano-hetero structures provide exceptional burn-up, reducing the waste products almost to their physical limits.

Compared with a CANDLE reactor burn-up of 40% of the uranium, the enhanced micro-nano hetero structured reactors is capable of improving this limit to 99% uranium burn-up. This burn-up greatly simplifies reprocessing and eliminates the proliferation concerns.

The FP extraction enhances the burn-up, but for a near 100% burn-up it is a challenge because of the criticality condition that should be satisfied, and material damage limits that have to be determined experimentally in order to assure the safety of the operation.

The plutonium used to aid the uniformity of the burning inside the active zone is recovered and can be utilised in subsequent fuels, raising some proliferation issues.

The fuel cycle is simplified by minimising the need for enrichment. Thorium fuel may be used as well, due to assisted plutonium recovered by the nano-clustered fuel.

The continuous separation of waste increases the leakage risk, but minimises the potential hazard of the leakage by having almost no fission product accumulation in the fuel.

The fission products are not entirely bad and useless materials; some of them have interesting properties and significant applications. Some of these products can only be stored. These products could be very precious assets in the future. The storage of the purified separated fission products is made easier because the required chemical stability can be assured.

In conclusion, the added plutonium provided by the micro-hetero fuel eliminates the need for separation and the need for spent fuel storage pools. It reduces to a minimum the waste fission products and simplifies their storage, replacing the geological disposition with storage as a valuable resource.

This new fuel cycle more completely utilises yellow cake as input for the cer-liq-mesh fuel production. The reactor burn-up provides fission product separation, minimal fuel reprocessing and useful isotope extraction and stabilisation. The hazard exposure is reduced by several orders of magnitude compared with existing fuel cycles.

Pure plutonium is a very valuable asset for the future of nuclear energy [20]. No fuel cycle aiming to completely utilise existing uranium and thorium reserves can do so without using the excellent properties of plutonium and higher fissionable actinides. The use of micro-hetero structure in singular wave reactors may transform this actual dream of nuclear people – to have a maximal burn-up of 100% and a minimal nuclear waste – into reality with the bonus that natural uranium and thorium, even spent fuel may be used directly with minimal need for enrichment.<sup>2</sup>

2. The structures presented are in the conceptual stage of development.



## References

- [1] Australian Uranium Association, *The Economics of Nuclear Power*, OECD/NEA, Paris (2007).
- [2] Nuclear Energy Agency (NEA), *Plutonium Fuel: An Assessment*, OECD/NEA, Paris (1989).
- [3] Smith, K., "Nuclear Fuel Prices Up 300%. Are You Hedged?" *Evolution Markets Executive Briefs*, 28 (2006).
- [4] Nuclear Energy Institute, "Uranium Fuel Supply Adequate to Meet Present and Future Nuclear Energy Demand", *Policy Brief* (2007).
- [5] Popa-Simil, L., "The Nuclear Progress and the Non-Proliferation Policies", *Proceedings of Global 2009*, Paris, France, 6-11 September (2009), Paper 9136.
- [6] The Uranium Institute, *Projected Costs of Generating Electricity*, SYM979899 (2000), AIEA.
- [7] Taube L., *Plutonium – A General Survey*, NEA (1974).
- [8] Weber, C.E., "Fuel Element Design", *J. Metals*, 8 (05-01), pp. 651-9 (1956).
- [9] Wacharasindhu, T., et al., "Liquid-semiconductor-based Micro Power Source Using Radioisotope Energy Conversion", *IEEE International Conference on Solid-state Sensors, Actuators and Microsystems*, Denver, CO, United States, pp. 656-659 (2009).
- [10] Weber, C.E., "Progress on Dispersion Elements", *Progress in Nuclear Energy*, 2 (Series 5, Metallurgy and Fuels) (1959).
- [11] Tolstolutskaia, G.D., et al., "Radiation Damage, Range Distribution and Site Location Measurements of Ar, Kr, Xe in Ni After Implantation and Annealing by Using Channelling Technique", *International Conference on Charged and Neutral Particles Channelling Phenomena* (2006), Frascati.
- [12] Popa-Simil, L., "Micro-structured Nuclear Fuel and Novel Nuclear Reactor Concepts for Advanced Power Production", *Progress in Nuclear Energy*, 50 (2-6), pp. 539-548 (2007).
- [13] Zigler, J.F., "Stopping of Energetic Light Ions in Elemental Matter", *Journal of Applied Physics*, 85, pp. 1249-1272 (1999).
- [14] White, D.W., et al., "Irradiation Behavior of Dispersion Fuels", *Fuel Elements Conference*, KAPL-P (1957).
- [15] Weber, C.E., "Dispersion-type Fuel Elements", *International Conference on the Peaceful Uses of Atomic Energy*, 9, p. 196 (1956) (United Nations).
- [16] Sekimoto, H., "CANDLE Burnup Regime After LWR Regime", *Progress in Nuclear Energy*, 50 (2-6), pp. 109-113 (2007).
- [17] Shwageraus, E., et al., "Use of Thorium for Transmutation of Plutonium and Minor Actinides in PWRs", *Nuclear Technology*, 147 (1), pp. 53-68 (2004).
- [18] Chen, X.-N., et al., "Fundamental Burnup Mode in a Pebble-bed Reactor", *Progress in Nuclear Energy*, 50 (2-6), pp. 219-224 (2007).
- [19] Formin, S.P., et al., "Initiation and Propagation of Nuclear Burning Wave in Fast Reactor", *Progress in Nuclear Energy*, 50 (2-6), pp. 163-169 (2007).
- [20] Trellue, H.R., "Neutronic and Logistic Proposal for Transmutation of Plutonium from Spent Nuclear Fuels as Mixed-oxide Fuel in Existing Light Water Reactors", *Nuclear Technology*, 147 (1), pp. 171-180 (2004).