Micro and nano flow usage in future nuclear reactors

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ABSTRACT

In nuclear reactors to mitigate the need for safety and the request for space of the fission products a new concept of micro-hetero nuclear fuel-structure has been developed. The new fuel design is based on micro-fuel beads with the dimensions smaller than the fission product range immersed into a drain liquid getting better thermal conductivity and less fission product damage. The drain liquid will interact with the fission products giving molecules with different buoyancy. The drain fluid it will transport outside the hot area of the nuclear reactor the fission products. To enhance the fuel-fluid interface and the micro-flow a nano-coating is applied over the fuel structure. The fluids are liquid metals like Lead Bismuth Eutectic; NaK salts operating up to 2000 K. The new microstructure resembles the biologic structures, in plants. The micro-heterostructure improves the thermal field distribution in the fuel eliminating the thermal stress damage and. the micro flow remove the fission products that "poisons" the reactor. The gains consist in the initial reactor mass reduction by 40%, fuel life increase up to 10 times, lower nuclear waste and unburned fuel immobilization reduction due to ultra high burnup factor.

Keywords: micro-hetero-structure, nuclear fuel, micro-flow, micro-bead,

1 INTRODUCTION

The nuclear power has more than 60 years of experience, becoming a mature technology. The further developments [1] of the nuclear fuel are difficult and expensive. The actual nuclear reactors lack of performances and the complexity and hazard of the fuel cycle is due to the lack of understanding and the past technologic capability of the nature law of energy distribution applied to fission. This is manifested by low burnup factor aggravated by the fuel's mechanical weakness.

The fission products accumulated in the fuel further are reducing its thermal conductivity and induce swallowing and crack shortening the fuel's life. Fig. 1 shows the complexity of fission products yield spectrum. To get 1 GwDay there is necessary to burn about 1 Kg of pure nuclear fuel, which produces about less than ½ liters of fission products, initially having about few percents of the delivered energy as radioactivity, but in several weeks this power reduces at less than few Kw/kg making the nuclear waste which has long decay time This may become the rare elements ore of future.

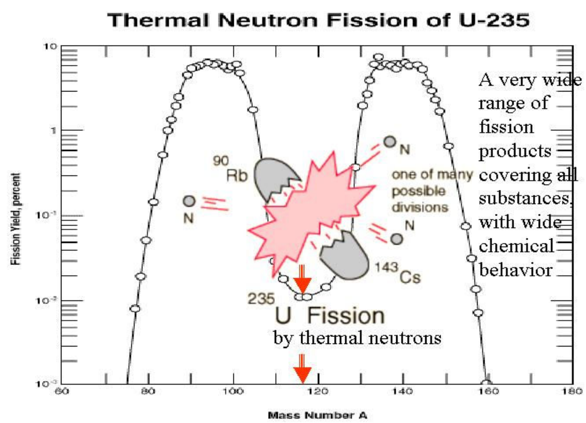

Fig. 1 – The complexity of fission products yield

2 THE MICRO-HETERO STRUCTURE

The solution to this problem drives toward a novel approach fundamentally new involving micro and nano sciences application. To eliminate the high fission product damage as the dispersion theory [2, 3] showed, the fuel beads have to be made shorter than the fission product effective stopping range. This is the high dispersion cermet approach which partially solves the problem, because it transfers the damage from the fuel to another material, a little bit more resistant, without mitigating the complexity of problems given by the fission product yield shown in Fig. 1.

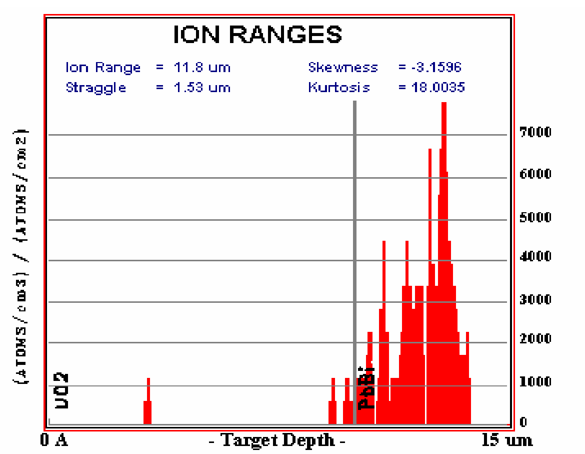

Fig. 2 – Fission product stopping range simulation

Fig. 2 shows the range of the stopping of the fission products into a solid – liquid hetero-structure [4].

The new fuel design is based on micro-fuel beads with the dimensions smaller than the fission product range immersed into a drain liquid. The liquid has the advantage of having better thermal conductivity than the ceramic fuel

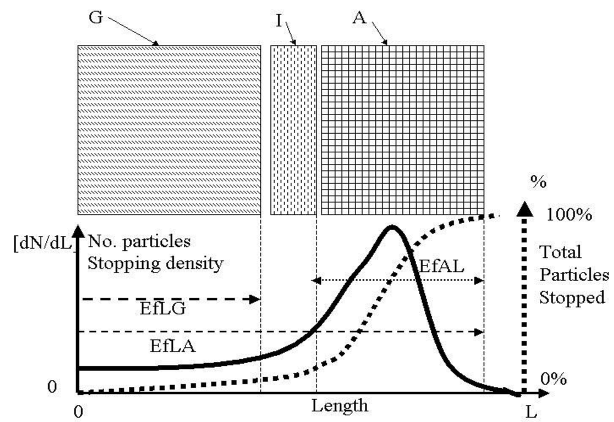

Fig 3

and can handle without damage the fission products stopping and heat deposition. Fig. 3 shows that a ternary generic structure was obtained, being composed of a central fission products generator, basically the nuclear fuel bead, coated by a protective layer generically named insulator and immersed into a fluid, which stops and collects the fission products.

The fission produces numerous radioactive isotopes with the masses symmetrically distanced from the median mass, as shown in Fig.1 having high and complex chemical reactivity. The immersion liquid will interact with the fission products giving molecules with different buoyancy that naturally trend to separate from the fluid. Imposing a slight movement to the fluid it will drain outside the hot area of the nuclear reactor the fission products.

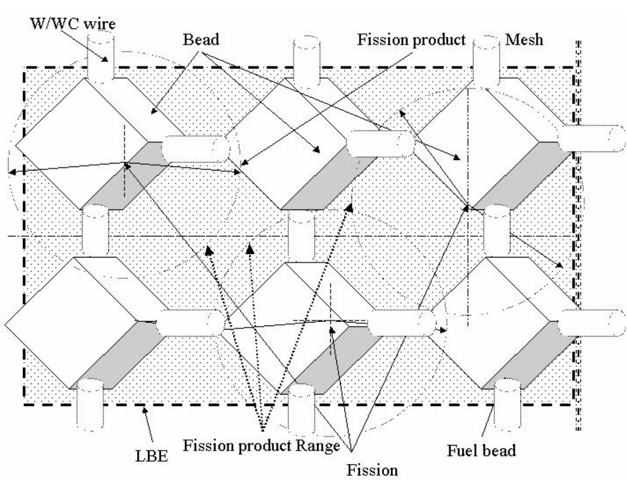

Fig. 4 – Nuclear fuel beads micromesh

The nano-fluidic flow has a high importance on the quality of extraction of the fission products. To enhance the fuel-fluid interface a nano-coating is applied over the fuel structure. Fig. 4 shows the design of the fuel element at the micro-bead level.

The nuclear fuel beads, which may be made of Uranium, Plutonium, and their combinations, as oxides, nitrides or carbides, are forming a bead on the cross of the refractory micro-wires in an elastic mesh.

The drain fluid flow has to be smooth, uniform and slow to give enough time to the short lives radioisotopes to disintegrate inside the nuclear reactor's hot zone, having less remnant radioactivity outside the reactor where it circulates through on-line separation purification equipment. The most preferred fluids are the Lead Bismuth Eutectic (LBE), or Sodium-Potassium NaK but other various liquid metals or salts operating up to 2000 K might be used. The advantages of the new microstructure, which

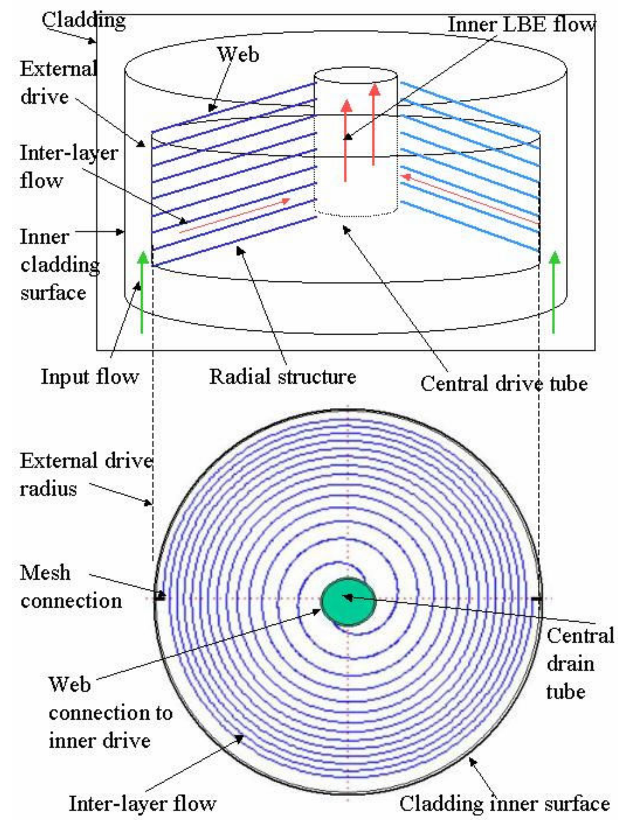

Fig. 5

resembles the biologic structures, like plants that transport continuously through their capillary structure all the substances needed for life, are significant.

Fig. 5 shows the structure of a fuel pellet made from the micro-beaded mesh. The drain liquid comes clean from the periphery, washes the fuel collecting the fission products and leaves the pellet through the central tube. First, the thermal field distribution in the fuel is ameliorating, eliminating the thermal stress damage. Secondly, the micro-flow is caring out the fission products that absorb neutrons "poisoning" the reactor. The consequence is that the mass of the reactor is reducing by more than 40%, and the lifetime of the fuel increases because the radiation damage is reduced by more than 90%. Another gain of the micro-fuel-fluid structure is the fuel compressibility feature to compensate for the burnup, and makes the burnup factor very high minimizing the nuclear waste and unburned fuel.

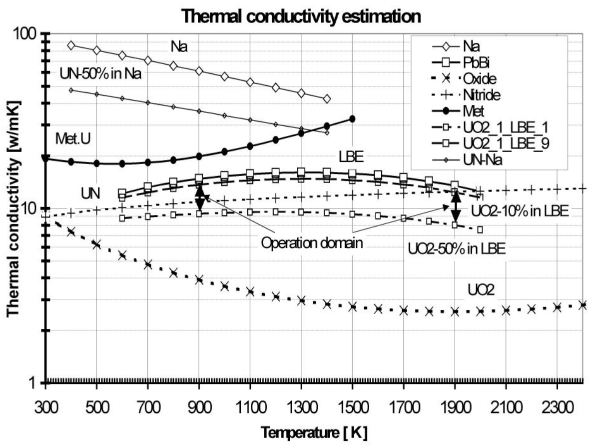

Fig. 6 – The thermal conductivity

The thermal conductivity is improved as shown in Fig.6 is improved by the mixing the beads with low thermal conductivity into liquid metal with higher thermal conductivity. Fig. 6 presents the case of UO_2 immersed in LBE, metallic beads immersed in NaK or Na. Other combinations are also possible. Another associated effect may be understood mixing Fig. 4 with Fig. 2 and 3, which shows that most of the fission products are stopping and depositing the radiation damage and thermal spike into the fluid surrounding the micro-bead.

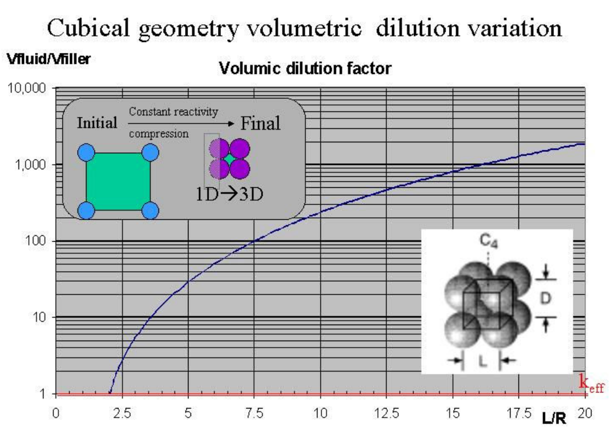

Fig. 7 – The compression of the fuel structure

The arrows defining the operation domain in Fig. 6 represent the case of a compressible fuel pellet as that shown in Fig. 5. By compressing the elastic mesh the fuel the relative concentration may be varied. If the criticality condition is reached for a lower concentration which means bigger interstices between the beads, and the fission products are removed by the drain fluid while the fissile material burn up, the fuel beads become lighter and relative fuel concentration decreases. By compressing the fuel there is possible to eliminate a part of the drain fluid and to bring back the fuel's concentration at the criticality requirement. The fuel pellet presented in Fig. 5 is also compatible to operate in shaped conical reaction tubes as in Fig. 8. In such a tube the drain fluid washes the beads and removes the fission products. The new fuel is introduced by a refractory

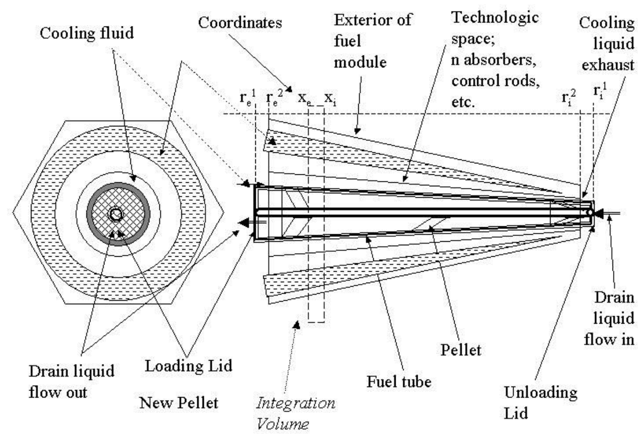

Fig 8 – Variable geometry nuclear reactor tube

robotic arm operating immersed in the drain liquid.
The tube's section is varying afte a fuel dependent law such as the burnup is compensated by pushing the fuel towards the small section end. As Fig. 7 shows the domain where the concentration may be kept constant is larger than 100:1. This feature assures an extraordinary burning factor to the fuel with more than 10 times better than the best obtained in present.
The flow in this structure is in the continuum domain, by applying the Knudsen criterion. The mean free path for liquid metals is in Angstrom domain, while the channel's dimensions are in microns.

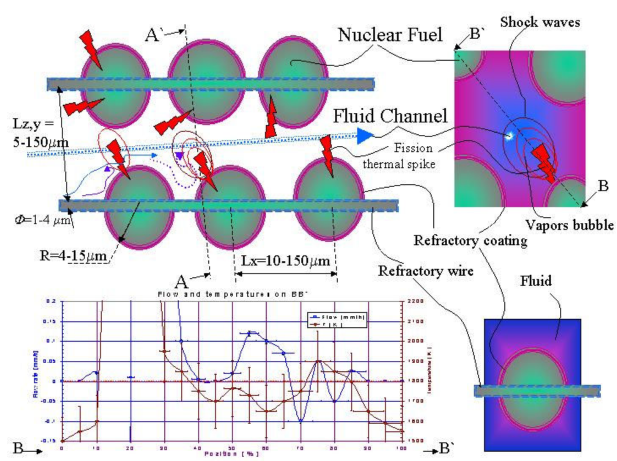

Fig. 9 – The micro-flow characteristics

Fig. 9 shows the structure of the fluid flow channel. The few tens microns in diameter nuclear fuel beads, coated into an separator material with the role to match the adhesion forces, are set on micron thick wires, and immersed in a liquid metal. The beads are cuasi-spherical and are mainly interlaced. There is no defined shape liquid channel, so any hydraulics number is difficult to be defined. More the fission acts generates thermal spikes that discharges a high power density of about 100 MeV into the fluid several tenths of cubic micron or les making it evaporate and re-condensate, similar to the cavitations process, but accompanied by a thermal and pressure shock waves. Navier-Stokes formulas are applicable in this case, but no analytical solution is possible. Special FEM method to characterize the flow into variable shape fluid channel, with continuously variable temperature, viscosity and pressure waves has to be developed. To this complexity, the modification of the fluid "turbidity" due to the occurrence of the fission products reacting with the fluid is adding several other parameters to consider. In Fig. 9 the cross-section AA` is presented in the upper right corner, where the temperature and fluid's speed is plotted for the diagonal cut BB` in the down-central part of the figure, while a section through the bead's elementary volume is given on the right side.

3 THE NANO-HETERO STRUCTURE

Another very important application for the nano-flow in nuclear reactor is the recoil-extraction breeding technology. Fig. 10 shows the schematic structure of a pellet, made usually of depleted uranium dioxide or carbide, micro powder made by a plasma jet, and stabilized into a PM gradient structure immobilized between micrometric meshes, generically called filters.

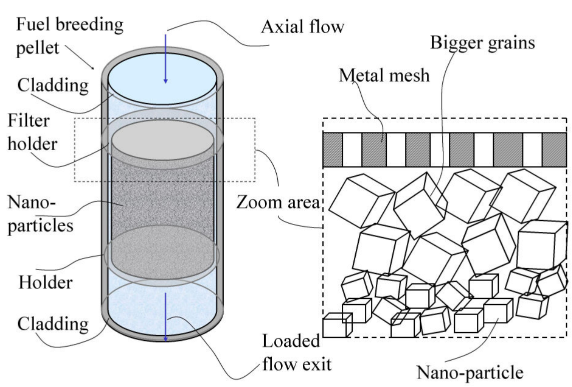

Fig. 10 – Super Grade Pu breeding pellet

The most important nuclear isotopes are the ^{233}Uranium obtained from ^{232}Thorium and ^{239}Plutonium obtained from ^{238}Uranium used in nuclear energy and ^{48}Vanadium ^{19}Florine positrons sources.
The simulation of nuclear collision and energy transfer shows that the impacted nucleus recoils in the interstitial space creating a Frenkel defect or lives small lattices. The Frenkel defect diffuses, and if no recombination occurs it stops at the lattices boundaries[5]. The nano-grains are self coated in thin layer to get a hydrophilic shell washed by the collection liquid, the particle is immersed. The efficiency of collection depends on particle magnitude and nuclear reaction channel parameters. For ^{239}Pu the direct recoil extraction rate is about 70% for $^{238}UO_2$ grains of 5 nm diameters and is brought up to 95% by diffusion due to ^{239}Nptunium incompatibility with Uranium dioxide lattice. Particles of 5 nm are hard to produce so a structure using particles of 100 nm have been tested. The $^{238}U^{16}O_2$ particles were obtained by plasma sputtering in oxygen atmosphere. The extraction efficiency is better due to diffusion that at moderate temperature places most of the breeding products out of the interface free to interact with the washing liquid. In this case, the fluid channel is also hard to be defined, but due to molecular interaction in some regions the flow ceases to be included into continuum domain, and shear flow occurs.
The advantage of the method and device is its ability of producing small amount of isotopic materials easy to separate, using the nuclear reactors, with higher yield than the accelerator based methods and requiring less chemistry.

4 CONCLUSIONS

The main advantages of the micro-hetero structure nuclear fuel system is related to the drastic increase in the performances of the actual nuclear reactors:

I. Longer fuel life (20-30 years)– up to 20 times
II. Enhanced fuel thermal conductivity, with lower radiation damage.
III. Higher temperatures (1000K<T<2500K) for higher efficiencies (50%<Eff<85%)
IV. New waste cycles with less waste (> 100 times reduction)
V. Higher burnup (up to >700 GwDay/ton of fuel theoretically possible)

The micro and nano flow simulations are more difficult in these structures due to the large number of variables spanning wide range of values, and high gradients of transitory phenomena.

The usage of the drain liquids makes nuclear reactors resemble the living beings because their operation patterns follow the nature models.

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