THE CONCEPTUAL DESIGN OF A DEMO-IMITATION SEPARATOR-THE MODEL OF A PLASMA MASS FILTER FOR IRRADIATED OXIDE URANIUM FUEL

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The design of a demo-imitation separator is presented which is the model of a plasma filter for the masses of irradiated oxide uranium fuel. Expected setup productivity is ~15…20 tons/year of the material – imitator, that corresponds to the production of SNF per year in WWER-1000 reactor. A non-radioactive multicomponent mixture of oxides of actinides, lanthanides, zirconium, molybdenum can be used as a working material for research. Depending on the state of the working material, the separator may have a horizontal or vertical position.

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INTRODUCTION

Magnetoplasma reprocessing of SNF, unlike the PUREX process used in industry, includes non-aqueous technologies, where only electricity is required, without increasing the volume of radioactive waste (RW). In [1] the sequence of stages for magnetoplasma reprocessing of spent nuclear fuel (SNF) is considered. The development of the concept of SNF magnetoplasma reprocessing involves the development of a plasma separator for cleaning of irradiated UO_2 from fission products (FPs).

To simulate the separation of nuclear fuel (NF) ions from FP ions in a plasma rotating in E⊥H fields, a demonstration - imitation separator (DIS-2) with a productivity equivalent to the production of SNF per year of WWER-1000 reactor (~ 20 tons/year) is being developed. In this paper, a conceptual design of the DIS-2 installation for experimental research is presented, with the possibility of further modernization into the industrial design. The setup design is based on the principles of plasma separation devices [2-4].

SIMFUEL [1] or its simplified modification - a non-radioactive multicomponent mixture consisting of oxides of actinides, lanthanides, zirconium, molybdenum, representing the main SNF components for conversion into plasma during magnetoplasma reprocessing can serve as a working substance for research. The three-dimensional model and the axial distribution of the magnetic field of this setup are shown in Fig. 1. The installation includes a plasma source, a magnetic system, a coaxial electrode system for generating an electric field E_r, a tuner, a pumping system, a cooling system, the longitudinal and end collectors. The longitudinal collector is located along the entire length of the vacuum chamber, and it is partitioned to separate the output areas of different masses. High vacuum in the separator chamber is provided by electric discharge , titanium sorbtion and condensation pumps.

Depending on the state of working substance, the installation may have a horizontal or vertical position. Since the main components of the working substance are oxides in the powder state, in this case it is advisable to use the unit in a horizontal position.

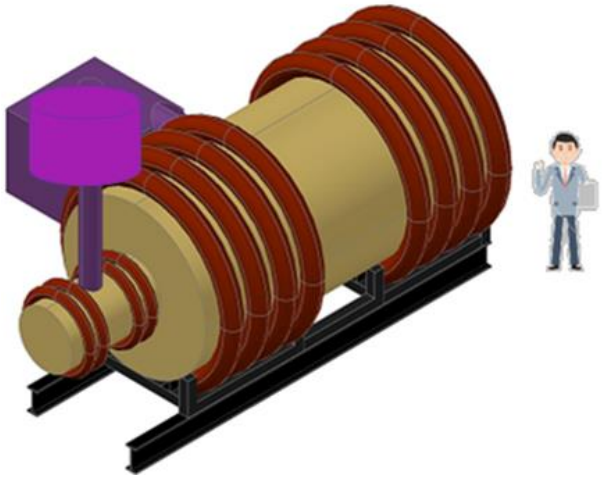


Fig. 1. 3D-model of DIS-2 setup (horizontal position). Dimensions: length ~ 5 m, diameter of the vacuum chamber ~ 2.6 m

If, conversion to plasma requires previous conversion of the working substance to the liquid state and its evaporation, then in the experimenal research the vertical arrangement of the installation can be used [1].

PLASMA SOURCE

When the setup is horizontally positioned, the working mixture in the form of a powder (UO_2, Nd_2O_3, ZrO_2, Ba, Mo, etc.) enters the plasma source (PS) in the transverse direction to the magnetic field induction (Fig. 2).

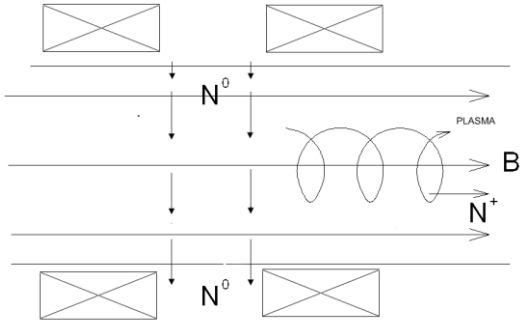


Fig. 2. Scheme of ionization area in the PS

The plasma parameters in the PS: $n_e \sim 10^{14}$ cm^{-3}, T_e~5 eV. The diameter of the exit hole in the PS is 10 cm. Magnetic field of a given configuration is provided by supercunducting (SC) winding. It is assumed that the charged particles are confined by the magnetic field of the PS and then injected into the plasma mass filter**.** The power of the PS is ~0.6 MW [5].

Our calculations consider symmetrical distribution of plasma, formed in the PS. However. we have to take into account that plasma can have asymmetrical distribution along the PS diameter (Fig. 3).

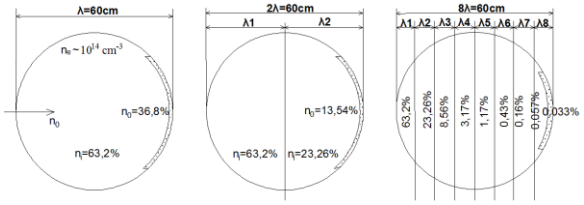


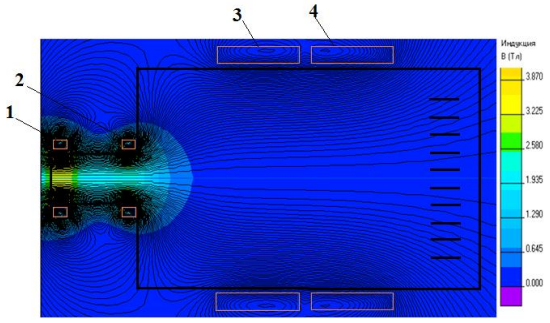
Fig. 3. Schematc view of asymmetrical plasma distribution in the PS

MAGNETIC SYSTEM

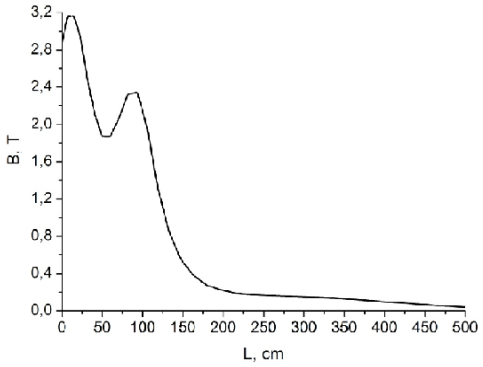
The magnetic system of the PS (Fig. 4) includes a system of two SC solenoids with parameters presented in Table. To obtain a high degree of plasma ionization in the PS, the magnetic field has a mirror configuration with maxima in the magnetic field distribution Bz ~ 3.5 and ~ 2.5 T for solenoid 1 and 2, respectively (see Fig. 4,a). When the plasma moves along axis in a decreasing magnetic field, the plasma flow expands, and in the separation area with a homogeneous magnetic field ~ 0.1 T (see Fig. 4,b), where the plasma is collisionless (n_e~$2\cdot10^{11}$ cm^{-3}), a spatial separation of heavy and light ions occurs. A homogeneous magnetic field in the separation area is provided by a thermal winding – solenoids 3, 4 Table.

Parameters of solenoids

Solenoid	Current density, A/m^2	Winding cross-section, m^2
1	$1.3\cdot10^8$	0.15
2	$9\cdot10^7$	0.15
3	10^6	1.90
4	10^6	1.90



a



b

Fig. 4. Axial distribution of the magnetic field for DIS-2 setup: a ~ image, b ~ graph

RADIAL ELECTRIC FIELD

A radial electric field, E_r is created by a system of coaxial electrodes. A feature of this system is the combination of a plasma rotation in crossed E⊥H fields with a resonance at the cyclotron frequencies of the target ions [3]. To solve this problem, the variable of the voltage component is used with a frequency equal to half of the cyclotron frequency for UO_2^+ ions. At the same time, the ion acceleration achieved and their moving to the localized region of the longitudinal collector. In this case, the resonant ions are uranium dioxide, that eject to the side chamber at a radius of R = 1.3 m at E_0 = 400 V/m, B = 0.1 T and addition of ac component $0.6E_0\sin(\omega t)$ at $\omega = ½\omega_{ci}$ (UO_2). The use of a tuner connected to a system of coaxial electrodes (Fig. 5) is necessary to solve this task. The tuner allows to set the required rf frequency for ac component of a radial electric field.

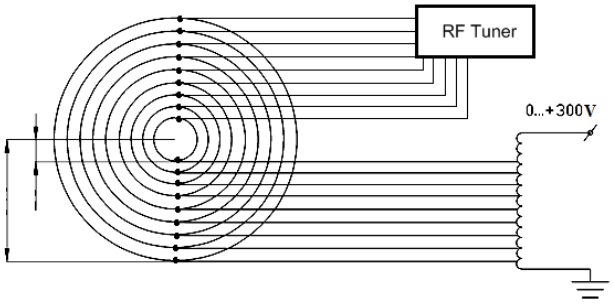


Fig. 5. Radial electric field system

CONDITIONS FOR PLASMA DEPOSITION OF FUEL IONS

The calculations carried out earlier [1] showed that at a radius of 1.3 m uranium dioxide ions is ejected into the sectional longitudinal collector in the region 3 (Fig. 6). In the case of incomplete ionization of the plasma, the neutrals are filtered out in the region 1 of the longitudinal collector. Heavy molecular ions (M> 400 a.m.u) eject to the lateral surface of the chamber in regions 2 and 4 (see Fig. 6). In addition, molecular ions including lanthanides: $Pr_2O_3^+$, $Nd_2O_3^+$, $La_2O_3^+$, etc. are deposited on the end collector as well as light FP ions: ZrO_2^+, MoO_3^+, Mo^+, etc.

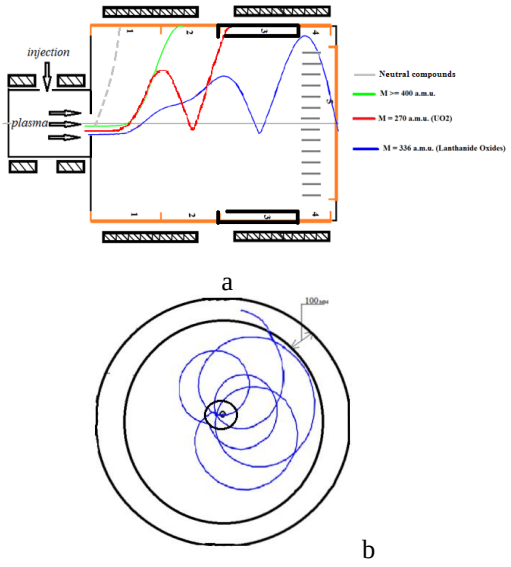


Fig. 6. The profile (a) and lateral section (b) of DIS-2 setup of horizontal position with ion trajectories for NF and FP ions at initial values: W = 5 eV, $\alpha = 45^0$, r =0.01 m, E_0=400 V/m and Eac=0.6 $E_0 \sin(\omega t)$ at $\omega = \frac{1}{2}\omega_{ci}$ (UO_2)

In this case, the resonant UO_2 ions increase their kinetic energy, which, according to calculations (Fig. 7), in the collector region is more than ~500 eV.

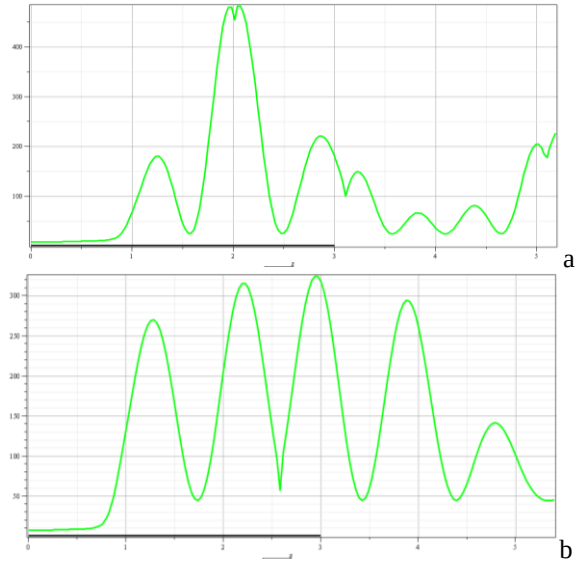


Fig. 7. The kinetic energy of molecular ions in DIS-2 setup: a – for UO_2 ions (m= 270 a.m.u.); b – for heavy FP ions (m = 400 a.m.u.)

Proceeding from the fact that the flux from the PS is ~ $1.1 \cdot 10^{21}$ particles, where 90 % are fuel ions, the estimated power of the FP ion flux to be deposited on the collector (Fig. 8,a) is ~ 100 kW. The square of section 3 for NF ions collecting is ~ 10^4 cm^2 (see Fig. 7,a). This can lead to a rather high specific heat load ~ 30 W/cm^2.

Estimates show that at a setup productivity of ~0.5 g/s (~ 20 tons/year) of the working mixture, the growth rate of deposited to the collector UO_2 layer can be ~ 0.5 mm/h. Following from the value of thermal conductivity for the uranium dioxide layer of ~$2.5 \cdot 10^{-2}$ W/cm·s at 1500^0C, deposition of the fuel ions would be carried out at high temperatures with decrease of the condensation coefficient and increase of the sputtering coefficient. To reduce the energy of the deposited ions, various methods are used: retarding potentials, creation of plasma decelerating targets, translucent absorbing filters, etc. In any case, this is an increase in the heat transfer surface. [6, 7]. In our case, it is proposed to develop a deposition surface due to the formation of a buffer region for ion collection (so-called "pocket") with an increase of a deposition surface in ~ 20 times. Fig. 8,b shows the "pocket" profile.

At uniform deposition of ions on the substrates located on the internal surface of the "pocket" special cooling of the "pocket" surface will not be required. In this case, at a plasma density of 10^{12} cm^{-3} in the buffer area, the energy will be dispersed over the entire surface of the "pocket" with S=16.5 m^2, and the specific heat load will be less than ~ 1 W/cm^2, which in equilibrium with radiation corresponds to ion deposition surface temperature ~350^0C.

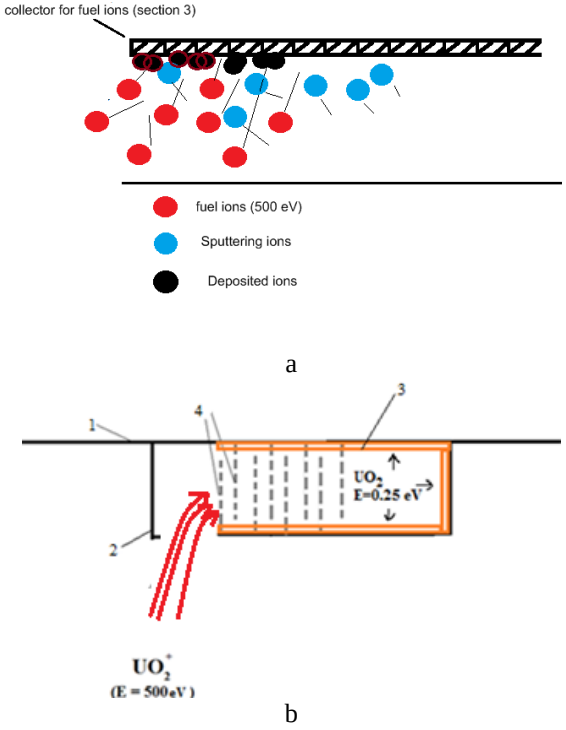


Fig. 8. The collector for fuel ions in DIS-2 setup: section 3 of the longitudinal collector (a); buffer area-"pocket" (b): 1 – vacuum chamber wall; 2 – outer collector wall; 3 – substrate for collecting nuclear fuel; 4 – tungsten grids

Homogeneous distribution of precipitations over the entire surface of the "pocket" can be realized using targets – a system of tungsten grids with high transparency. Estimation of the heating temperature for grids in the "pocket" region for the specific ion flux density varies from 350 to 750^0C. However, the precipitations will not be strictly uniform over the surface of the "pocket". So, it is impossible to fill up the buffer area completely. Estimates show that non-stop operation of DIS-2 setup is possible during the week with filling the "pocket" by a quarter.

CONCLUSIONS

An alternative technique to the PUREX process, which is used in industry is magnetoplasma SNF reprocessing with reduction of RW amount for repository from 100 to 5 %. For developing the concept of magnetoplasma SNF reprocessing a design of a demo-imitation separator is presented which is a model of a plasma filter for the masses of irradiated oxide uranium fuel.

The feature of the experimental setup is the combination of plasma rotation with resonance at the cyclotron frequencies of the target ions. The resonant ions are UO_2^+ that are filtered out to the lateral surface of the chamber by addition of ac voltage component that leads to an increase of their kinetic energy to a value of ~500 eV. To solve this problem it is proposed to enlarge the ion deposition surface of the buffer area ('pocket') in ~20 times. This allows to decrease specific heat load and increase condensation coefficient. For the uniform UO_2^+ deposition on the substrates along the inner surface of the 'pocket' it is assumed to use the system of tungsten grids with high transparency located along the length of the 'pocket'. The grids provide operational regime of the experimental setup without cooling of the deposition surface. The estimated temperature of the 'pocket' surface varies from 350 to 750^0C, that is acceplable for carrying out the experiments.

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КОНЦЕПТУАЛЬНЫЙ ПРОЕКТ ДЕМОНСТРАЦИОННО-ИМИТАЦИОННОГО СЕПАРАТОРА – МАКЕТА ПЛАЗМЕННОГО ФИЛЬТРА МАСС-ОБЛУЧЕННОГО ОКСИДНОГО УРАНОВОГО ТОПЛИВА

В.Б. Юферов, В.О. Ильичева, В.В. Катречко, С.В. Шарый, А.С. Свичкарь, М.О. Швец, В.И. Ткачев, Д.В. Винников, А.Н. Озеров

Представлена конструкция демонстрационно-имитационного сепаратора, который является моделью плазменного фильтра для масс-облученного оксидного уранового топлива. Ожидаемая производительность установки составляет ~ 15…20 тонн на год материала-имитатора, что соответствует наработке ОЯТ в год реактора ВВЭР-1000. В качестве рабочего материала для исследования может использоваться нерадиоактивная многокомпонентная смесь оксидов актиноидов, лантаноидов, циркония, молибдена. В зависимости от состояния рабочего материала сепаратор может иметь горизонтальное или вертикальное положение.

КОНЦЕПТУАЛЬНИЙ ПРОЕКТ ДЕМОНСТРАЦІЙНО-ІМІТАЦІЙНОГО СЕПАРАТОРА – МАКЕТА ПЛАЗМОВОГО ФІЛЬТРА МАС-ОПРОМІНЕНОГО ОКСИДНОГО УРАНОВОГО ПАЛИВА

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Представлено конструкцію демонстраційно-імітаційного сепаратора, що є моделлю плазмового фільтра для мас-опроміненого оксидного уранового палива. Очікувана продуктивність установки складає ~ 15…20 тонн на рік матеріалу-імітатора, що відповідає виробленню ВЯП на рік реактора ВВЕР-1000. Як робочий матеріал для дослідження можна використовувати нерадіоактивну багатокомпонентну суміш оксидів актиноїдів, лантаноїдів, цирконію, молібдену. В залежності від стану робочого матеріалу, сепаратор може мати горизонтальне або вертикальне положення.