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ON THE POSSIBILITY OF OBTAINING A BEAM OF HEAVY IONS IN THE FORM OF AN "OPEN UMBRELLA" WITH SUBSEQUENT DEPOSITION IN THE SEPARATOR MANIFOLD

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The study of SNF reprocessing is impossible without obtaining and studying a multicomponent, low-energy and complex ion beam of an "umbrella" shape. The beam is obtained from a plasma flow created in a plasma source (PS) with a magnetic field of about 3 T, flowing along the axis into a weak magnetic field, at a level of 0.1…0.5 T. At the same time, its density decreases, and the entire energy of the plasma is converted into a jet directed along the axis. To randomize the particles of the jet plasma, a reflecting magnetic field is further placed on the axis. Without changing direction, the plasma flows in a hollow magnetic force tube around a solenoid with a reverse magnetic field. In this region, ions are drawn out in the radial direction towards the annular hole of the "pocket". The target ions, M (230-277) follow umbrella trajectories and, being neutralized, are deposited in the "pocket" on the inner walls, the remaining ~ 3% are scattered and remain on the walls of the separator.

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INTRODUCTION

In Ukraine, ~50% of electricity is produced at nuclear power plants. Previously, spent nuclear fuel, SNF, was stored and processed in the Russian Federation (Krasnoyarsk), at present it is stored in the storage facilities of operating nuclear power plants. The chemical technology of SNF reprocessing is used in the world, [1] which requires chemical reagents such as acids and alkalis, but most importantly, 2000 t of water is required for 1 t of SNF. This technology is used in France, England and the Russian Federation, but is not applicable in Ukraine due to its population and the isolation of the Black Sea basin. We are developing a plasma method for reprocessing SNF for subsequent recycling of fuel in reactors, and so far it only requires electricity in the amount of ~ 5% produced by the reactor. Similar work is being carried out in the USA and Russia. Of course, it is difficult to assume that it will be completely possible to do without chemistry, but it is advisable to strive for this.

DESIGN FEATURES OF THE SNF REPROCESSING SYSTEM

In [2, 3], the process of extracting actinides deposited in a "pocket" was considered. As already mentioned, the ion beam of the SNF plasma separator, complex in composition and configuration, is created by a dense plasma ~ $10^{13}…10^{14}$ cm^{-3}. This plasma includes UO_2, oxides of actinides, lanthanides, zirconium, uranates, and other compounds supplied to the PS in powder form. The magnetic field in the region of plasma creation has a value of about 3 T [4]. 25% of the volatile compounds have already been separated by this time at the heating stage.

Further, this plasma moves through the emission hole into a sharply decreasing magnetic field, down to 0.1…0.5 T, (Fig. 1). In this case, the plasma parameters change significantly, both in terms of density and temperature T_e, T_i. With a sharp drop in the magnetic field, T_i transforms into the longitudinal velocity of the plasma jet, which is in a longitudinal incident magnetic field. Further, after the reflecting magnetic field, the plasma moves symmetrically around the Z axis, where, with the help of Er, ions are extracted and separated in crossed electric and magnetic fields (see [7] and Fig. 1).

Thus, it is assumed that the actinide beam with a half-wave trajectory has the form of an "umbrella" with a thickness along the Z axis, – d about ~ 10…30 cm. What is equal to – nr_L-Larmor radii of actinide oxides (Fig. 2). That is, in a cylindrical system, the beam traveling along the axis abruptly begins to diverge. This means that it moves symmetrically along the angle θ around the axis and the radius R. A certain distance passes simultaneously along the Z axis – d, (determined by the rate of heavy ion pulling into the separation region and the diffusion of ions in the plasma, which goes after collisions in the magnetic field of the plasma flow reflection region) (see Fig. 1).

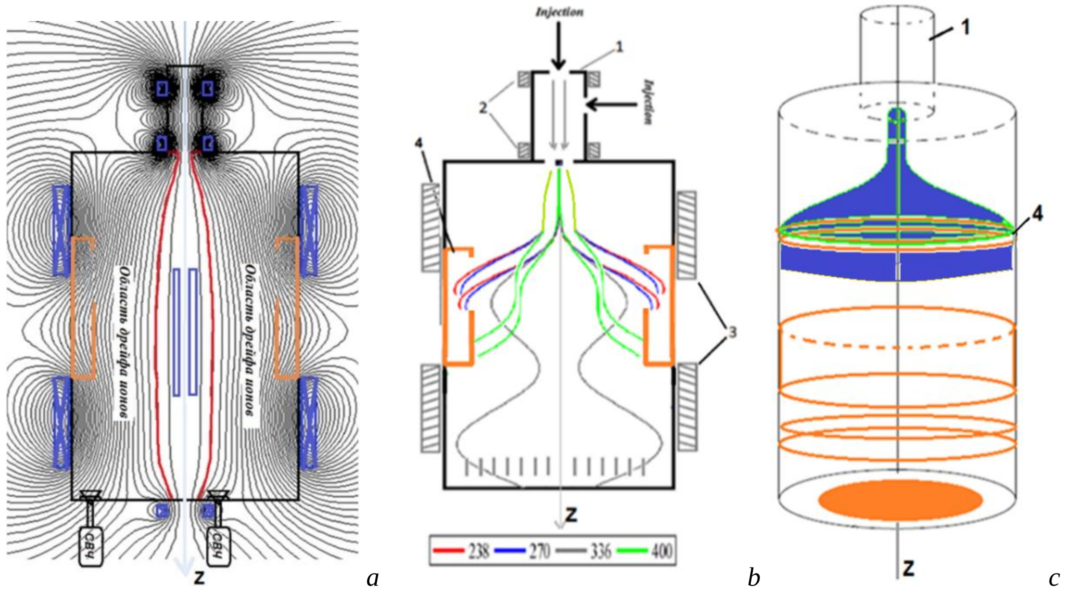
ION AND ELECTRON CURRENTS IN COMPENSATING PLASMA

In [4], when extracting ions or electrons from a plasma separately in a flat geometry and a longitudinal magnetic field, the values of the electron and ion currents are determined by the Childe-Langmuir equation:

$$J_e[A/cm^2] = \sqrt{2}/9\pi \cdot \sqrt{e/m_e} \cdot U^{3/2}/d^2\ [V/cm] = 2.33 \cdot 10^{-6}\ U^{3/2}/d^2;$$
$$J_{H+}[A/cm^2] = \sqrt{2}/9\pi \cdot (2e/m_H)^{0.5}\ U^{3/2}/d^2 = 5.46 \cdot 10^{-8}\ m_H^{-0.5}\ U^{3/2}/d^2\ [V/cm];$$
$$J_{z+}[A/cm^2] = \sqrt{2}/9\pi \cdot (2e/M_z)^{0.5}\ U^{3/2}/d^2 = 3.39 \cdot 10^{-9} m_H^{-0.5} U^{3/2}/d^2, \quad (1)$$

where $m_e = 1/1850\ m_H$, m_e is the mass of an electron, m_H^+ is the mass of a hydrogen ion, proton, M_z^+ is the mass of the target ion, J_{ei} is the current of electrons, ions, d is the cathode-anode gap, U is the voltage.

In this case, the electron current is many times greater than the ion current. This is determined by the ratio of the masses of the electron and ion-proton, which differ by thousands of times. And for heavy ions (lanthanides and actinides) – hundreds of thousands of times. In the formula [1], this ratio is under the square root, but still varies from 43 for hydrogen to 774, for example, for the lanthanum oxide ion – $La_2O_3^+$.



(1 – PS; 2 – PS solenoids; 3 – separator solenoids; 4 – manifold for collecting actinides)
Fig. 1. View of the separation system: a – magnetic field lines with an additional internal solenoid; b – trajectories of ions of various masses: 238, 270, 336, 400; c – umbrella trajectories of actinides

Currents of electrons and ions of different masses calculated using the Childe-Langmuir equation

A/cm^2	$U=10^3$ V, d=1 cm	$U=10^4$ V, d=1 cm	$U=10^4$ V, d=0.33 cm
J_e	$77{\cdot}10^{-3}$	2.3	23.0
J_1^+ (Hydrogen)	$1.4{\cdot}10^{-3}$	$4.5{\cdot}10^{-2}$	0.45
J_{270}^+ (UO_2)	$9\ 10^{-5}$	$3.6{\cdot}10^{-3}$	$3.6{\cdot}10^{-2}$

From Table it follows that with an emission area – $S \sim 10^4$ cm^2, which is obtained around the reflecting solenoid, it is possible to draw out an ion current of ~ 300 A (M = 270), which is necessary for processing 20 t / year of SNF.

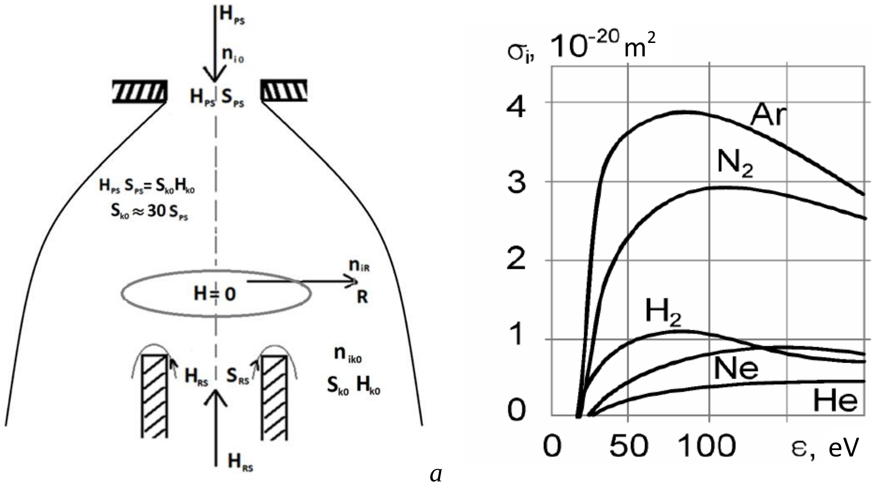
Taking into account the Bursian problem [4], we obtain the Langmuir-Boguslavsky equation for the case of different anode and cathode sizes. The beam stretching in this case proceeds along the magnetic field. The dependences are the same, only the coefficients change, ~ 8 J_e [4]. A similar problem was also solved by Pierce [4]. Here the magnetic field is also longitudinal, although the electric field is at an angle of 67.5°. Here, only the coefficients ~20 J_e, will also differ [4].

In our case, the magnetic field is almost perpendicular to the beam motion. Therefore, the coefficients must also be taken into account. To determine their value, it is advisable to conduct experiments. Previously, the calculation of beam ion trajectories was for the collisionless case, i.e. beam ions do not electrically influence each other [6]. But in reality, the space charge is too large, and the beam current (A/cm^2) and its divergence will be quite noticeable. Therefore, to neutralize the charge, electrons with a density of $(1\ldots5)\cdot10^{11}$ cm^3 are needed.

For the above density, the mean free paths are at the level of one to several meters. Since it is necessary to reduce the scattering of beam ions, the neutralizing plasma should consist of light elements, hydrogen or helium, and have a low temperature, but occupy almost the entire space where the beam of target ions moves. To do this, in the area of transportation of the actinide ion beam, see the geometry of Fig. 1, plasma must be formed, for example, by the microwave method (at present, this method is widely used to create low-temperature plasma in small volumes). The ions of this plasma must have a mass much smaller than the mass of the beam ions in order to reduce scattering during collisions. It is proposed to use hydrogen or helium for plasma formation, that is, the mass ratio of the beam target ions is ~100 times greater for hydrogen and ~70…80 for helium. Initially, it was assumed that hydrogen plasma is more preferable due to the smaller mass of ions. However, it should be taken into account that the low-temperature microwave hydrogen plasma is molecular, with H_1^+, H_2^+, H_3^+ ions. It is also necessary to take into account the energy of vibrational and rotational levels. Based on these considerations, He_4^+ plasma, in terms of energy, may be more preferable. This will require an experimental comparison of both cases. However, as can be seen from Fig. 2 [4], the dependences of the cross sections and ionization thresholds of hydrogen and helium on energy differ significantly.

Due to the smallness of the Helium ionization cross section, it will be necessary to significantly increase the density of He^0 neutrals (to obtain a given He^+ plasma density). This will immediately increase the collisions and scattering of heavy ions on helium, increasing the energy. Therefore, let us consider hydrogen plasma. If in the energy calculation of hydrogen plasma, it is necessary to take into account rotational and vibrational levels, then for helium plasma, it is necessary to take into account recombination radiation. In addition, the ionization potential of He atoms = 24.5 eV, which is twice as high as hydrogen. It is possible to calculate the dynamics of this plasma in a mirror trap created by the separator's magnetic field. The second level of ionization of He^{2+}, apparently, should not be taken into account.

In both cases, it will be necessary to take into account both energy and recharge losses: energy difference between ions, light with energies (~ 1…10 eV) and heavy (50…300 eV), as well as the efficiency of using the "umbrella" beam. For helium ions, the deposition on the walls of the separator chamber of the material of the umbrella beam is additionally increased. Therefore, due to the lack of many data on the cross sections and excitation and scattering energies, the calculation of the energy costs for both cases of He and H_2 will now give underestimated values.



a *b*

Fig. 2. a – magnetic field lines with a reflective electrode; b – energy dependences of the cross sections for ionization of atoms and molecules by electrons

Balance equations for hydrogen plasma for neutrals n_{H2} and ions n_{H1}^+, n_{H2}^+, n_{H3}^+ i.e. values dn_{H2}/dt=, dn_{H1}^+/dt=, dn_{H2}^+/dt=, dn_{H3}^+/dt=, we take from [5] respectively for $n_{H2}^0=(1…3)\cdot 10^{11}$ cm^{-3} (Fig. 3).

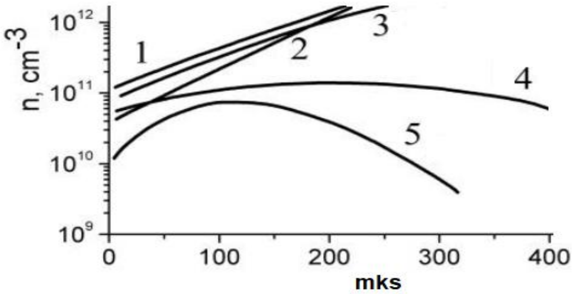


Fig. 3. Values of the hydrogen plasma density in time ($1 - n_e$; $2 - n_{н1+}$; $3 - n_{н10}$; $4 - n_{н2+}$; $5 - n_{н3+}$)

MAGNETIC FIELD AND SEPARATOR PLASMA

Let us consider the separator plasma in a magnetic field, its magnitude and features. The electrons, e^-, are magnetized. Ion magnetization must be considered separately. The Larmor radius of the hydrogen ion m_{H1} $r = 144\,(m_{H1}E)^{0.5}/H$ should be less than 1 cm, which satisfies our case for T_i=4 eV and H=0.1 T.

However, for the magnetization of ions with a mass of 270, the value of H should be about 0.5 T. Naturally, the reflective solenoid must have no less field, although it is desirable to test larger values. In addition, it should be taken into account that in the plasma jet from PI, in addition to ions of oxides of actinides and lanthanides, etc., there will be oxygen ions, O_1^+ O_2^+ and even O_3^+ and, of course, negative ions too. Metal ions will also be present. All these ions will be sent towards the hydrogen plasma. And if before that there was no free oxygen (if there was, then in small quantities), now free water necessarily appears, as well as its OH radical. This water must be pumped out. Based on these considerations, helium plasma has additional advantages over hydrogen plasma.

CONCLUSIONS

1. The magnetic configuration of the SNF separator turns out to be quite complex and consists of several parts:

a. The plasma source must create a plasma jet of complex configuration ions in a magnetic field of 3…5 T. In this case, the plasma jet is multicomponent and is obtained from a powder with a particle size of 50…150 microns.

b. Large magnetic separator system where beam ions are separated by mass. This system also holds hydrogen (or helium) plasma, which neutralizes the charge of the heavy ion beam.

c. An additional solenoid with a magnetic field reversed in direction, reflecting the plasma jet and chaoticating it.

2. Given the complex design of the system, its operation must be optimized for individual nodes:

a. Investigate the movement of plasma.

b. To study the features of creating an "umbrella" beam of ions deposited inside a closed cavity, the so-called "pocket". Later, actinides are obtained from this pocket in the form of a powder, i.e. secondary, processed nuclear fuel.

c. Investigate the charge stabilization of the beam and the possibility of its controlled movement along the axis. This is necessary for its entry into the "pocket", the deposition of the primary beam there and the dynamics of back scattered flows (neutrals).

d. Explore the possible advantages of helium or hydrogen plasma, taking into account the retention in the separator tube.

e. Select the geometry of the solenoid, the distance from the PS and the value of the reflecting magnetic field, taking into account the plasma density and the field strength of the PS solenoid.

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ПРО МОЖЛИВОСТІ ОТРИМАННЯ ПУЧКА ТЯЖКИХ ІОНІВ У ФОРМІ «РОЗКРИТОГО ЗОНТИКА» З НАСТУПНИМ ОСАДЖЕННЯМ У КОЛЕКТОРІ СЕПАРАТОРА

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Вивчення переробки ВЯП неможливе без отримання та вивчення багатокомпонентного низькоенергетичного та складного іонного пучка «парасолькової» форми. Пучок виходить з потоку плазми, створеного в джерелі плазми (ДП) з магнітним полем близько 3 Тл, далі втікає по осі в слабке магнітне поле, на рівні 0,1…0,5 Тл. Його щільність зменшується, і вся енергія плазми перетворюється на струмінь, спрямований уздовж осі. Для хаотизації частинок струминної плазми на осі додатково розміщується магнітне поле відбивного соленоїда. Не змінюючи напрямки, плазма тече в порожній магнітній силовій трубі навколо соленоїда зі зворотним магнітним полем. У цій області іони витягуються у радіальному напрямку до кільцевого отвору «кишені». Цільові іони М (230-277) слідують «парасольковими» траєкторіями і, нейтралізуючись, осідають у «кишені» на внутрішніх стінках. А решта, ~3%, розсіюються і залишаються на стінках сепаратора.