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DELVING INTO SOME SPECIFIC FEATURES OF THE MAGNETIC SYSTEMS USED FOR THE PLASMA RECYCLING OF THE SPENT NUCLEAR FUEL (SNF)

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Consideration was given to some specific issues of the development of magnetic systems intended for the SNF plasma separators to separate, extract and deposit the actinides and also to magnetic systems of a different purpose, in particular plasma source (PS), isotope separation system and low – temperature compensation system, including plasma jet (PJ) preparation system designed for the creation of an "umbrella-like" ion beam and for the film deposition in the "pocket".

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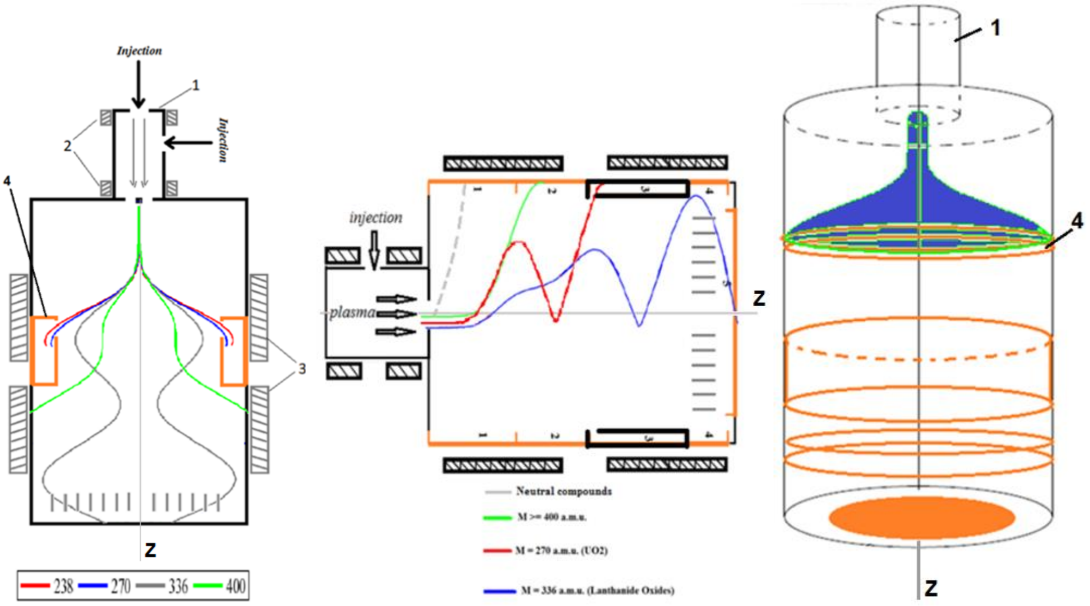
Papers [1–5] give consideration to some issues of the creation of the magnetic plasma separator for the spent nuclear fuel (SNF) to realize the closed nuclear fuel cycle. It was mentioned earlier [6] that the first thermal stage of treatment allows for the partial 75% removal of fission products at relatively low temperatures (to 2500 °C), and after this treatment the SNF contains only actinide oxides, lanthanide and zirconium oxides. To convert actinides, lanthanide and zirconium including their oxides and complex ions (urinates, etc) to the plasma state we need to have the temperatures higher than those required for the uranium dioxide melting. Consideration was given to the two versions of plasma separators, i.e. with horizontal and vertical arrangements. These are given in Fig. 1 and both types can be used for separation purposes.

Let's recollect the principle of the separator operation. The ion beam of a complex composition and configuration initiated by the SNF plasma separator is created by the dense plasma ($10^{13}…10^{14}$ cm^{-3}) in the plasma source. The magnetic field (MF) created by PS coils has a value of 1 to 3 T. The plasma moves through the emission orifice to the abruptly diminishing MF of 0.1 T and starts to expand (see Fig. 1).



a *b* *c*

(1 – PS; 2 – the magnetic system of PS; 3 – the magnetic system of the chamber of the magnetic plasma separation; 4 – Nuclear fuel (NF) collector)

Fig. 1. Vertically arranged magnetic plasma separator (a); horizontally arranged magnetic plasma separator (b); volumetric (spatial) distribution of the actinide ion beam in the separator chamber (c)

In this case, the plasma parameters such as density and temperature change significantly. The plasma ions acquire the directed velocity v_z. Similar to the PS cathodes, plasma has a negative potential and the ions start to get accelerated by the potential layers of external electrodes. The force magnetic lines transfer the potential to accelerated ions through the plasma of a n_i order 10^{11} cm. Having different masses these acquire different velocities and angles of incidence and follow different spatial trajectories.

Actinide ions have similar masses (m = 235…277) and exceed 95% of the total number of plasma ions of the SNF. Their motion in the vacuum chamber of the separator forms the so-called "umbrella" beam. It is mainly propagated along the radius and partially along the axis and it is entrapped by the input orifice or "the pocket". At the same time it starts to decelerate its speed with the defocusing effect due multiple collisions of these ions with each other and the walls and depositing in the long run on the internal walls of the collector. As the ions move to the separator chamber the ion flow density is decreased along the radius. However, it is still relatively high about 1 A/cm^2. Due to this fact, the forces of the volumetric charge that propagate the beam are rather high and these should be neutralized. In other words, for the actinide ions to get to the pocket or to the collector the positive charge of the beam ions should be neutralized by the electrons. For this purpose, the charge neutralizing plasma should be formed in the actinide ion beam transportation domain. However, the mass of the ions of this plasma should be much lower than that of beam ions to decrease the beam scattering during the collisions. For this purpose, we suggest to use the hydrogen or helium targets. We will not give consideration to the ion behavior in "the pocket", it was described in [7]. However, the attention should be paid to the fact that after the condensation of the appropriate amount of actinide particles on the walls these should be removed or evacuated. It can be done in the following way. To remove the solid-state product, in particular actinides and their oxides with the masses of (m = 235…277) it is reasonable to use the vertical system (Fig. 2).

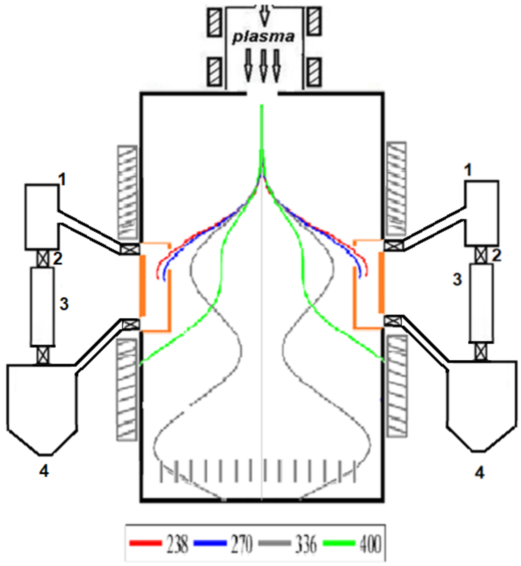


Fig. 2. Vertical magnetoplasma WNF separator with the actinide removal system (1 – compressor; 2 – vacuum transitions; 3 – vacuum pump; 4 – the reservoir for the evacuated powder-like N)

The UO_2 layer deposited on the collector walls is rather monolithic. When heated to T = 550 °C, it is transformed to the powder-like state. For these purposes we will use the O_2 and Ar gas mixture flow, where oxygen provides the chemical reaction of the volume oxidation with the formation of the higher U_3O_8 oxide and argon acts as the gas carrier that also provides the safe fuel oxidation. U_3O_8 being converted to the powder-like state easily falls down to external containers during the moderate vibration and the internal surface of the pocket becomes empty and ready for the collection of another deposited layer. The volumetric cracking occurs due to a considerable difference in the specific weights of UO_2/U_3O_8, accordingly 10.5/8.5 g/cm^3.

We suggest realizing all that using a single processing cycle. For this one processing cycle, the collector or pocket volume should correspond to 20 t of SNF/year for the density of 10.5 g/cm^3 or 2 m^3 (for the absolutely filled volume). The sediment thickness should not exceed 1…1.5 cm changing no layer deposition coefficient value and it means that the inverse flow value from "the pocket" is also not changed. Therefore the sediment area should be equal approximately to (0.6…1) 10^6 cm^2. It means that the pocket can have a size of about: D=4.9 m, L=1.5 m, d=0.2 m.

Since the separator is designed for the recycling of the SNF in amount of 20 t/year we need to create PS with the equivalent current of 300 A/year. As a result, even the umbrella-like beams (see Fig. 1,c) have the high densities of low energy in the restricted domain. It results in powerful electric fields that have a defocusing effect onto these beams. Therefore, the separation domain, or the so-called magnetic mirror requires the plasma to prevent the beam defocusing effect.

The life time of plasma in magnetic mirrors depends also on the appropriate enduring relationship value of MF. Therefore it is reasonable to give consideration to the topography and specific features of the magnetic systems of the separator. Fig. 3 gives such a system with the solenoid on the axis symmetric to the PS. Based on the computations of the MF for the additional solenoid we tabulated the data in Table and Fig. 4. To do computations, the field value of the additional PS was taken in proportion to that of the solenoid field of the PS: x1.0, x0.5, x0.25 for the two r values: on the axis (r=0) and on the half-radius of the separator (r=65 cm).

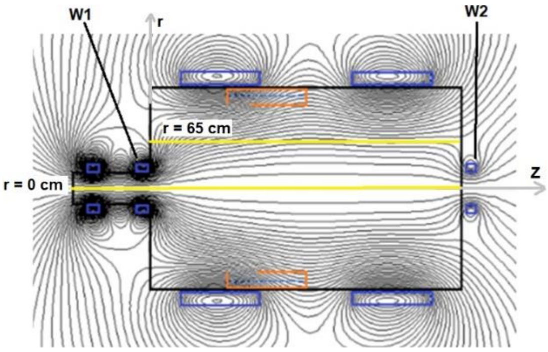


Fig. 3. Force lines of the MF with the solenoid on the axis (W2) symmetrical to the PS, with the magnetic field value equal to 0.25x of PS (W1)

Maximum values of magnetic fields at different ratio values of the magnetic fields of coils on the axis (r=0) and in the domain (r=65 cm)

MF ratio	r = 0 (see Fig. 4,a)		r = 65 cm (see Fig. 4,b)	
W2/W1	**T**	**%**	**T**	**%**
1	2.33185	363	0.1138	112
0.5	1.14242	227	0.10541	104
0.25	0.50323	100	0.10158	100

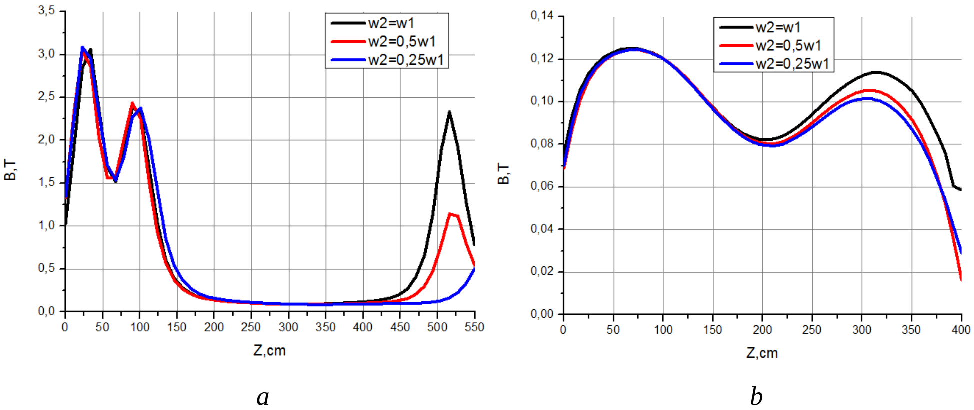


Fig. 4. Longitudinal distributions of the magnetic field at different value ratios of MF (a – axial distribution (r=0); b – radial distribution (r=65 cm))

To stop the directed plasma flow escaping from the PS the solenoid of a small diameter with the counter field can be placed in the separation chamber along the axis. However, it will actually not change the distribution in the separation area and the enduring relationship value won't decrease due to a small internal diameter and weak fields. Fig. 5 shows the location of the solenoid in the system.

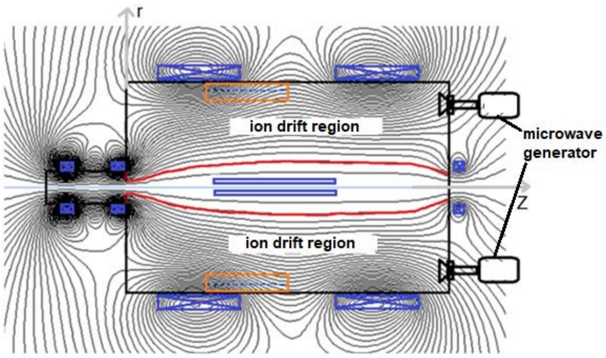


Fig. 5. Force lines of the MF with the additional internal solenoid

The electrons in the MF of the separator are magnetized and move along the MF force lines. Therefore, the embedment of the additional solenoid with the counter-connection regarding the PS solenoids and separator will allow for the redirection of the ordered motion of the electrons closer to the separation domain. It solves partially the problem of the formation of positive volumetric charge that we face due to the selective heating of the major ions of NF in ExH fields and later on the problem of their trajectories with the output to the collecting pocket at the first half-wave of the loop with the pocket located on Z = 100…200 cm.

CONCLUSIONS

1. Magnetic configuration of the separator is rather complicated and it consists of four unit systems: a –

magnetic system of the separator; b – magnetic system of the PS; c – the symmetric PS solenoid to increase enduring relationship value. These three systems taken together make up the magnetic complex of a direct plasma trap. The configuration also includes: г – the reflecting solenoid to reflect and scatter the plasma jet initiated by the PS. The enumerated components should create the umbrella-like ion beam.

2. To actualize this model we need:

- to study the plasma motion from the PS and the possibility of the creation of the umbrella-type ion beam taking into consideration the suggested system;
- to study the charge stabilization of the beam, an opportunity for its controlled motion, the motion along the axis, input to the pocket (z = 0…30 cm), deposition and dynamics of inverse flows;
- to study the holding of the plasma in the magnetic mirror of the separator and define the advantages of the helium plasma in comparison to the hydrogen plasma.

3. Conceptual papers [8–10] give consideration to the recycling of the SNF with the output of 20 t/year. This system is suitable for the WWPR-1000 reactor and in its turn it requires substantial material inputs and long adjustment period. Today, we can experimentally create the beams at the level of 10…15 A instead of wanted 300 A (i.e. about 1 g ions per second).

Therefore, the real output will be considerably decreased to 100 kg/year. It should be noted that it is applicable not to the stationary source operating conditions but to pulse-mode operation conditions of the PS. This problem arises due to the non-availability of appropriate energy systems and the diagnostics. However, it can be done in the pulsed mode. Time processes for the plasma and ion separation last tens of mikroseconds. The PS and the MF of the separator embrace the millisecond range. The ion beam compensation lasts for 10…15 A with the density of ~ 10 мA/cm^{-2} and the plasma density of $(1…2)\cdot10^{11}$ cm^{-3} is quite real for the free motion length of ~ 2…3 m. Energy inputs to maintain the compensating plasma will not exceed 5 to 10 kW. The size of simulation and experimental unit can considerably be reduced. However, the mentioned problems still exist. We need to provide the charge compensation of the umbrella-like beams and their input to the collecting pocket.

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ПРО ДЕЯКІ ОСОБЛИВОСТІ МАГНІТНИХ СИСТЕМ ПЛАЗМОВОЇ ПЕРЕРОБКИ ВІДПРАЦЬОВАНОГО ЯДЕРНОГО ПАЛИВА (ВЯП)

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Розглянуто деякі питання створення магнітних систем плазмових сепараторів ВЯП для розділення та вилучення осаджених актиноїдів. Також розглянуто магнітні системи для різного призначення: плазмового джерела (ПД), поділу ізотопів та низькотемпературної компенсуючої плазми, підготовки плазмового струменю ПД для створення «зонтичного» іонного пучка та осадження плівок у «кишені».