METHODS OF ENRICHING URANIUM – 235

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Abstract: Nuclear energy has become a source of energy which has a huge role in human life. Most reactors collect energy emitted from controllable fission chain reaction of ^{235}U. However, as well as other materials, we need to conduct several processing steps before using ^{235}U. In this report, we present the concepts, principles, advantages and disadvantages of several typical methods of enriching ^{235}U, such as gas diffusion, thermal diffusion, isotope separation by laser of plasma, gas centrifuge, …, an important step in the processing of transform an ore deposit into energy to serve the human life.

Keywords: *uranium – 235, enrichment, gas diffusion, thermal diffusion, laser isotope separation, plasma separation, gas centrifuge.*

I. GENERAL ABOUT URANIUM AND ENRICHMENT

1. Uranium

Uranium - discovered in 1789 by the German chemist Martin Heinrich Klaproth - is a silvery-white metallic chemical element in the actinide with atomic number 92. Uranium has six isotope, the most common of which are ^{238}U (146 neutrons) and ^{235}U (143 neutrons). All isotopes are unstable and uranium is weakly radioactive.

In nature, uranium is found as ^{238}U (99.2742%), ^{235}U (0.7204%), and a very small amount of ^{234}U (0.0054%).

Fig.1. Uraninite, also known as Pitchblende

2. Conversion and refining

The rocks may have only a few percent (normally < 0.3%) uranium in them. The uranium then has to be removed from the rock and concentrated. The milling process involves crushing and pulverizing the rock into very fine fragments and adding water to create a slurry. This slurry is then mixed with sulfuric acid or an alkaline solution to release the uranium from the host rock. From this acid or alkaline solution, uranium oxide or yellowcake is precipitated.

Fig.2. A drum of yellow cake (a mixture of uranium precipitates)

3. Enrichment of ^{235}U

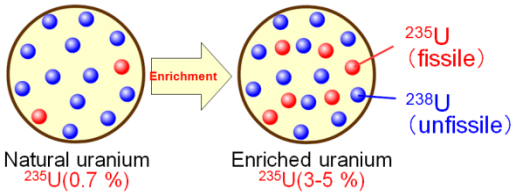

Fig.3. Enrichment of ^{235}U

Enrichment ^{235}U is increase the percentage of ^{235}U in natural uranium.

Uranium found in nature consists largely of two isotopes: ^{235}U and ^{238}U. Isotopes ^{235}U and ^{238}U are chemically identical, but differ in their physical

properties, notably their mass. The difference in mass between ^{235}U and ^{238}U is about 3u, which allows the isotopes to be separated and makes it possible to increase or 'enrich' the percentage of ^{235}U, cause all present enrichment processes, directly or indirectly, based on this small mass difference.

Natural uranium contains only 0.7% ^{235}U. Nuclear reactor fuel is typically enriched to contain approximately 5% ^{235}U. Uranium used for nuclear weapons would have to be enriched at least 90% ^{235}U. Uranium was enriched to 20% or more ^{235}U is called HEU (high-enriched uranium). Uranium enriched above the natural ^{235}U abundance but to less than 20% is called LEU (low-enriched uranium).

4. Separative work unit

A separative work unit (SWU) is a unit of measurement used in the nuclear power industry, just as unit measurements such as calorie, watt, decibel, ampere, volt, etc.., are used in other industries.

II. METHODS OF URANIUM ENRICHMENT

1. Geseous diffusion

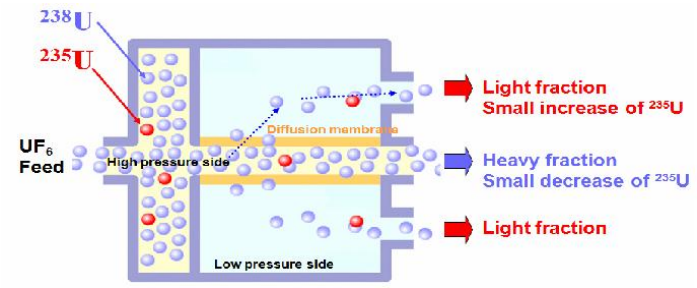

Fig.4. Gaseous diffusion

Diffusion membrane has pores of 8-10 nm

The diffusion process involves forcing uranium hexafluoride gas under pressure through a series of porous membranes or diaphragms. As $^{235}UF_6$ molecules are lighter than the $^{238}UF_6$ molecules they move faster and have a slightly better chance of passing through the pores in the membrane, possibly manufactured from sintered powdered nickel. The UF_6 which diffuses through the membrane is thus slightly enriched, while the gas which did not pass through is depleted in ^{235}U.

The molecules of the lighter gas will have a higher average speed than the heavier molecules for the same kinetic energy: $E = \frac{1}{2} M_{^{235}UF_6} v^2_{^{235}UF_6} = \frac{1}{2} M_{^{238}UF_6} v^2_{^{238}UF_6}$

The ratio of the velocities becomes: $\frac{v_{^{235}UF_6}}{v_{^{238}UF_6}} = \sqrt{\frac{M_{^{238}UF_6}}{M_{^{235}UF_6}}}$

For a mixture of two gases since the diffusion rates are proportional to the molecules velocities, the separation factor for the instantaneous diffusate, called the ideal separation factor α is inversely proportional to the square root of the molecular weights, and is given by:

$$\alpha = \sqrt{\frac{M_{^{238}UF_6}}{M_{^{235}UF_6}}}$$

Using the molecular weight of uranium hexafluoride:

$$M_{^{238}UF_6} = 238 + 6\times19 = 352$$
$$M_{^{235}UF_6} = 235 + 6\times19 = 349$$
$$\rightarrow \alpha = \sqrt{\frac{352}{349}} = 1.00429$$

All components of a diffusion plant must be maintained at an appropriate temperature and pressure to assure that the UF_6 remains in the gaseous phase. The gas must be compressed

at each stage to add pressure which was lost when gaseous UF_6 through the diffuser, then must be cooled before entering the next. The requirements for pumping and cooling gas make diffusion plants enormous consumers of electric power. Because of this, gaseous diffusion is the most expensive method currently used for producing enriched uranium.

2. Electromagnetic isotope separation (EMIS)

One of the earliest successful enrichment technique was electromagnetic isotope separation, in which large magnets are used to separate ions of the two isotopes.

Magnetic separation depends on the principle of the mass spectrometer.

$M_{U^{235}}, M_{U^{238}}$ are mass of ion ^{235}U and ^{238}U respectively. $R_{U^{235}}$ and $R_{U^{238}}$ are the circular radii of the path taken by ^{235}U and ^{238}U respectively.

After some calculations we have the ratio of the radii can also be written as:

$$\frac{R_{U^{235}}}{R_{U^{238}}} = \sqrt{\frac{M_{U^{235}}}{M_{U^{238}}}}$$

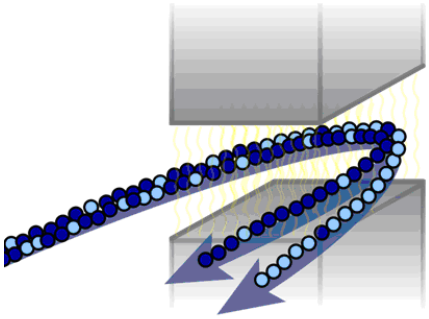

Fig.5. Electromagnetic isotope separation (EMIS) - Schematic diagram of uranium isotope separation in a Calutron (a device, developed in 1940 to produce HEU) shows how a strong magnetic field is used to redirect a stream of uranium ions to a target, resulting in a higher concentration of ^{235}U (represented here in dark color) in the inner fringes of the stream.

This shows that the isotopes of different masses will move in trajectories with different radii. These radii are proportional to the square root of the masses. Collectors can be placed at these radii to collect the different nuclei. These devices can generate very little quantities of isotopes. EMIS is a process that can produce weapons grade material from natural uranium in only two stages. However, hundreds to thousands of units would be required to produce large quantities of HEU because of the process's relatively low product collection rate and the long cycle time required to recover material between runs.

3. Thermal diffusion

The kinetic theory of gases predicts that gases have different molecular weight diffuse with different rates. In this process, a gas compound rises as it heats, down as it cools, and separates into it lighter and heavier components.

Applied to uranium enrichment, a gaseous uranium compound such as uranium hexafluoride is circulated in an annular region between two vertical pipes kept at different temperatures. The lighter molecules of $^{235}UF_6$ and $^{234}UF_6$ get more concentrated near the hot surface where they are carried upward by the convection current. An exchange occurs with the current moving downward along the cold surface producing a fractionation process. After a state of equilibrium is reached, the gas near the upper end contains more of the light molecules than near the lower end.

The thermal diffusion process is characterized by its simplicity, low capital cost, and high heat consumption.

4. Laser isotope separation (LIS)

Atomic and molecular laser isotope separation techniques use lasers to selectively excite atoms or molecules containing one isotope of uranium so that they can be preferentially extracted.

Photon's energy: $E_{photon} = hf = \frac{hc}{\lambda}$

Ionizing energy: $E_{ionization} \sim Z$

Although LIS appears promising, the technology has proven to be extremely difficult to master and may be beyond the reach of even technically advanced states.

Common name for such processes include:

- First category: atomic vapor laser isotope separation (AVLIS).

- Second category: molecular laser isotope separation (MLIS).

AVLIS process is based on the fact that ^{235}U atoms and ^{238}U atoms absorb light of different frequencies (or colors). Although the absorption frequencies of these two isotopes differ only by a very small amount (about one part in a million; for example, the ^{238}U absorption peak shifts from 502.74 nm to 502.73 nm in ^{235}U), the dye lasers used in AVLIS can be tuned so that only the ^{235}U atoms absorb the laser light. As the ^{235}U atom absorbs the laser light, its electrons are excited to a higher energy state. With the absorption of sufficient energy, a ^{235}U atom will eject an electron and become a positively charged ion. The ^{235}U ions may then be deflected by an electrostatic field to a collector. The neutral atoms ^{238}U pass through the product collector section and are deposited on a tails collector.

The idea for the MLIS process was conceived by a group of scientists at the Los Alamos National Laboratory in 1971. There are two basic steps involved in the MLIS process. In the first step, UF_6 is irradiated by an infrared laser system operating near the 16 mm wavelength, which selectively excites the $^{235}UF_6$, leaving the $^{238}UF_6$ relatively unexcited. In the second step, photons from a second laser system (infrared or ultraviolet) preferentially dissociate the excited $^{235}UF_6$ to form $^{235}UF_5$ and free fluorine atoms F. The $^{235}UF_5$ formed from the dissociation precipitates from the gas as a powder that can be filtered from the gas stream.

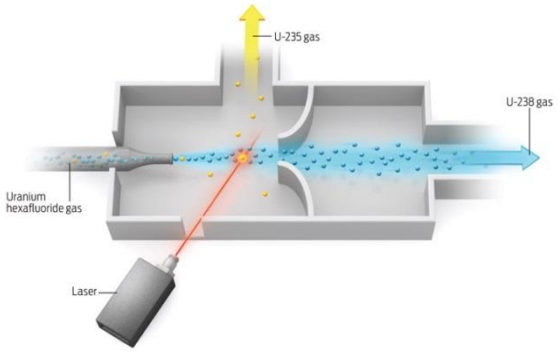

Fig.6. Scheme of laser isotope separation

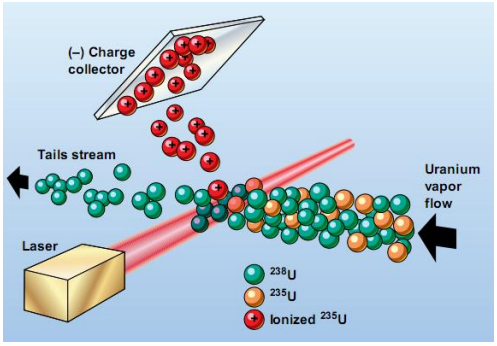

Fig.7. Scheme of molecular isotope separation

5. Plasma separation

The plasma separation process has been studied as a potentially more efficient uranium enrichment technique to use the advancing technologies in superconducting magnets and plasma physics.

In this process, the principle of ion cyclotron resonance is used to selectively energize the ^{235}U isotope in plasma containing ^{235}U and ^{238}U ions. A feed plate of solid uranium serves as the source of neutral uranium atoms. These atoms are vaporized by bombarding the plate with energetic ions in a process called sputtering. A microwave antenna located in front of the plate energizes free electrons which collide with neutral uranium atoms in the vapor sputtering off the plate. This takes electrons from the uranium atoms and produces plasma of ^{235}U and ^{238}U ions.

The plasma is subjected to a uniform magnetic field along the axis of a cylindrical vacuum chamber as the plasma flows from source to collector. The magnetic field is produced by a superconducting magnet located around the outside of the chamber. The high-strength magnetic field produces helical motions of the ions, with the lighter ^{235}U ions spiraling faster and having a higher ion cyclotron frequency than the heavier ^{238}U ions. As the ions move toward the collector, they pass through an electric field produced by an excitation coil oscillating at the same frequency as the ion cyclotron frequency of the ^{235}U ions. This causes the helical orbit of the ^{235}U ions to increase in radius while having minimal effect on the orbit of the heavier ^{238}U ions. The plasma flows through a collector of closely spaced, parallel slats, the physical appearance of which roughly resembles a venetian blind. The large orbit ^{235}U ions are more likely to deposit on the slats, while the remaining plasma, depleted in ^{235}U, accumulates on an end plate of the collector. PSP is a process that would require several stages to produce HEU from natural feed.

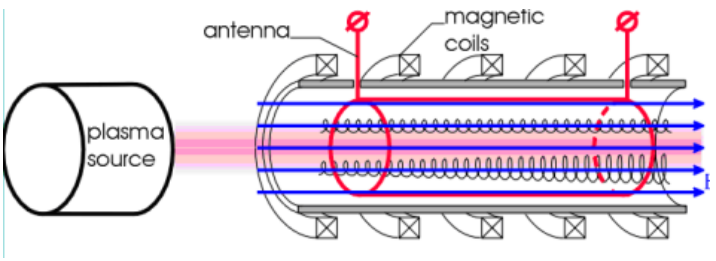

Fig.8. Scheme of plasma separation

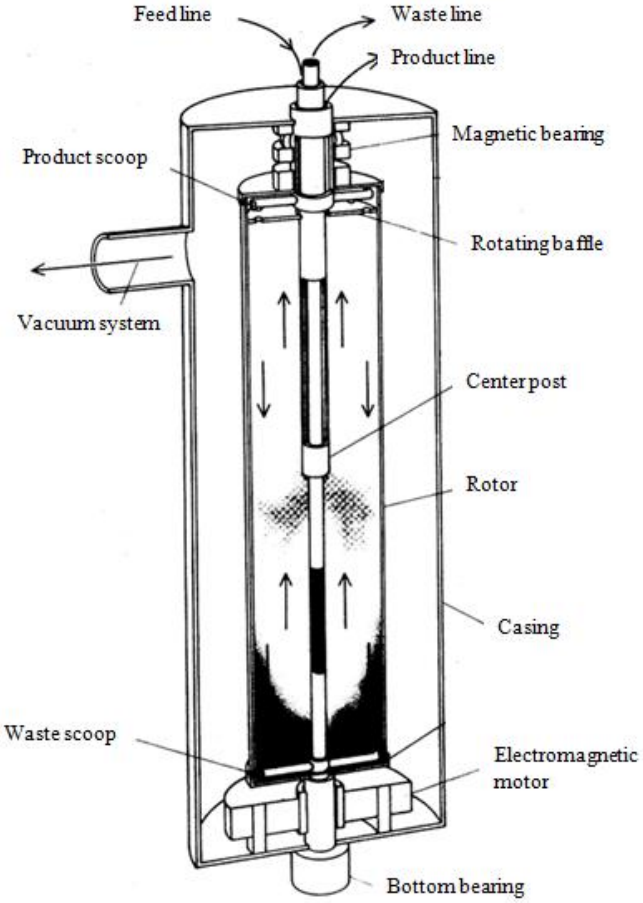

Fig.9. Interior details of a gas centrifuge. The vertical arrows inside the rotor represent the internal gas circulation.

6. Gas centrifuge

Nowadays, in the uranium enrichment industry, the gas centrifuge method is most used to enrich ^{235}U, because it requires only about 5% of the power compare with others methods.

Gas centrifuge have two main components: rotor and stator. Gas (UF_6) is pumped into rotor. The rotation of rotor creates centrifugal force, which separates isotopes of uranium, base on the small difference mass between ^{235}U and ^{238}U isotopes.

To realize the behavior of the flows inside the rotor, some complex equations in hydrodynamics and separation theory need to be considered. Typically, the Onsager's Master equation and the diffusion – convection equation need to be considered.

The Onsager's Master equation: $$\frac{\partial^2}{\partial\xi^2}\left\{e^{\xi}\frac{\partial^2}{\partial\xi^2}\left(e^{\xi}\frac{\partial^2\chi}{\partial\xi^2}\right)\right\}+B^2\frac{\partial^2\chi}{\partial\eta^2}=0$$

The diffusion – convection equation:

$$\rho_{eq} w \frac{\partial x}{\partial z} = \frac{\rho D}{r} \frac{\partial}{\partial r}\left[r \frac{\partial x}{\partial r} + \frac{\Delta M \Omega^2}{RT_0} r^2 x(1-x) \right] + \rho D \frac{\partial^2 x}{\partial z^2}$$

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CÁC PHƯƠNG PHÁP LÀM GIÀU URANIUM – 235

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Tóm tắt: Năng lượng hạt nhân đã trở thành nguồn năng lượng có vai trò to lớn trong cuộc sống con người. Hầu hết các lò phản ứng đều thu năng lượng tỏa ra từ chuỗi phản ứng phân hạch có kiểm soát của U-235. Tuy nhiên, cũng như các nguồn nguyên liệu khác, ta cần tiến hành nhiều bước xử lý trước khi có thể sử dụng được U-235. Trong khuôn khổ báo cáo này, chúng tôi trình bày các khái niệm, nguyên lý cũng như ưu khuyết điểm của một số phương pháp làm giàu U-235, điển hình như khuếch tán khí, khuếch tán nhiệt, tách đồng vị bằng laser hoặc plasma, khí ly tâm, …; một bước quan trọng trong quá trình biến đổi một loại mỏ quặng thành năng lượng phục vụ cuộc sống con người.