# Understanding and Model Development of Gas Centrifuge Enrichment Process

Yonhong Jeong*, Seung-hyo Yang, Hojung Do, Yein Seo
*Center for Nuclear Nonproliferation Strategy & Technology, Korea Institute of Nuclear Nonproliferation and Control, 1418 Yuseong-daero, Yuseong-gu, Daejeon 34101, Republic of Korea*
**Corresponding author: jyh1404@kinac.re.kr*

## 1. Introduction

Countries operating nuclear facilities have their nuclear fuel cycles, and there may be differences in the range of facilities that can be operated or detailed processes depending on the country's circumstances. However, it shares the flow of a typical nuclear fuel cycle: Enrichment, Fabrication, In-core Depletion, Reprocessing, and Disposal. Among them, nuclear cycle facilities directly related to the diversion of nuclear weapons are enrichment and reprocessing. In particular, in the case of enrichment facilities, it is easy to hide the fact that they have facilities and operate them, so it can be said to be an essential facility in evaluating a state's nuclear capabilities. However, in the case of South Korea, as the uranium enrichment facility itself is a special nuclear cycle facility, it does not have actual operation experience, and access to the facility or access to detailed process information is limited, so it is better to simulate and evaluate it through a virtual model. It will provide an instrumental framework of perception from the point of view of understanding a nation's nuclear capabilities.

## 2. Basic Theory

An enrichment capability called a separative work unit (SWU) is commonly used to estimate uranium production at uranium enrichment facilities. [1] However, there is a fear that such an estimation formula may overestimate or underestimate the actual ability because it is too simple to understand the actual phenomenon. The gas centrifuge enrichment method uses the principle that isotopes are separated according to the difference in mass between uranium isotopes based on a pressure gradient using centrifugal force. Using this as a basic formula, the difference in isotope concentration in the centrifuge can be calculated, and finally, the following formula can be obtained. [2]

$$0 = D\rho \frac{1}{r}\frac{\partial}{\partial r}\left[\frac{\Delta M}{2RT}\left(\frac{v_a}{a}\right)^2 r^2 N(1-N) + r\frac{\partial N}{\partial r}\right] - \rho w \frac{\partial N}{\partial z} + D\rho\frac{\partial^2 N}{\partial z^2}$$

$D$ : self-diffusion coefficient
$\rho$ : density
$\Delta M$ = 0.003 kg/mol
$R$ : the universal gas constant
$T$ : average temperature
$N$ : isotope concentration
$p$ : pressure

$$\delta U_{Rost}(K) = \frac{1}{2}K\left(\frac{\Delta M}{2RT}v_a^2\right)^2\left[1-\left(\frac{r_1}{r_2}\right)^2\right]^2\left(1-\exp\left[\frac{2\pi D\rho}{\ln(r_2/r_1)}\frac{Z}{K}\right]\right)^2$$

$$K = F\frac{(1-\theta+L/F)^2}{\theta(1-\theta)}$$

$F$ : feed rate
$L$ : countercurrent rate
$\theta$ : cut, the ratio of up-flow rate to feed rate

Also, the total amount of uranium and the total amount of U-235 are kept constant within the process according to the mass balance equation: [3]

$$Uranium\ Balance : F = P + W$$

$$U-235\ Balance : F \times N_F = P \times N_P + W \times N_W$$

$F$ : cascade feed rate
$P$ : cascade product rate
$T$ : cascade tails rate
$N_F$ : U-235 concentration of feed stream
$N_P$ : U-235 concentration of product stream
$N_T$ : U-235 concentration of tails stream

Since a single centrifuge alone cannot achieve sufficient concentration, commercial facilities can connect them in parallel or series to achieve the desired level of volume and concentration. In this way, many centrifuges are configured in a cascade form to perform separation work repeatedly. In an ideal cascade, it is assumed that the mixing effect is minimized because the concentration in the depleted flow at the top and the concentrated flow at the bottom are the same. [4]

$$\delta U = F\frac{\sqrt{\gamma}-1}{\sqrt{\gamma}+1}\ln\sqrt{\gamma} \qquad \gamma = \frac{N_P/(1-N_P)}{N_W/(1-N_W)}$$

## 3. Model Development

Based on the mathematical model of the physical behavior discussed so far, a simulation model that can evaluate the enrichment capacity of the enrichment facility was developed. Of course, the problem is simplified through many assumptions to increase modeling efficiency. The assumptions made are as follows.

- The model is composed of stage units, not centrifuge units.
- The detailed specifications of the centrifuge are assumed to be P-2 type
- Assume the ideal cascade
- Assume that 90 %-HEU is obtained through the series connection in the same cascade
- The scope of modeling is limited to the cascade hall, not the entire facility

The gas centrifugation uses uranium hexafluoride ($UF_6$) in a gaseous state as process material, so detailed process modeling is performed using The AnyLogic's Fluid Library. The stage is assumed as the most basic unit of modeling, and the stage can be understood as a structure in which separated elements are connected in parallel. [5] Stages are connected in series to form a cascade. For the P-2 type centrifuge, a cascade of 4 stages is connected in series to produce 90 % HEU, and a secondary cascade is connected to recycle the intermediate by-products (concentration: 1.5 %, 10 %, 40 %, etc.).

In order to simulate the mass flow in the completed cascade, it is necessary to set the main input variables such as the separation work unit and the production compared to the input of the separation factor. However, to set the variable's initial value, the procedure shown in Figure 1 must be performed first.

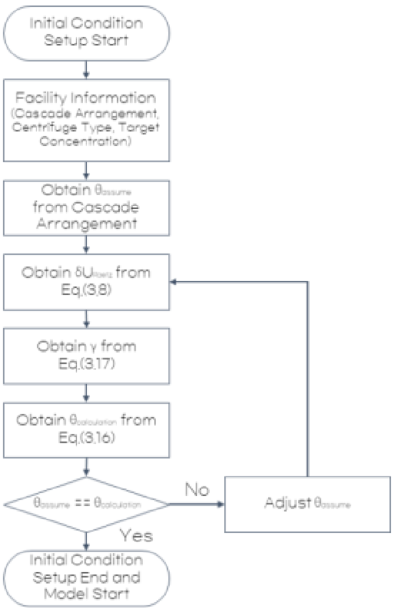


***Figure 1. Initial variable setting process***

### 4. Modeling Results

The operation screen of the simulation model is shown in Figures 2 and 3. The results of estimation of production in the case where the intermediate product exists and where it does not exist are as follows.

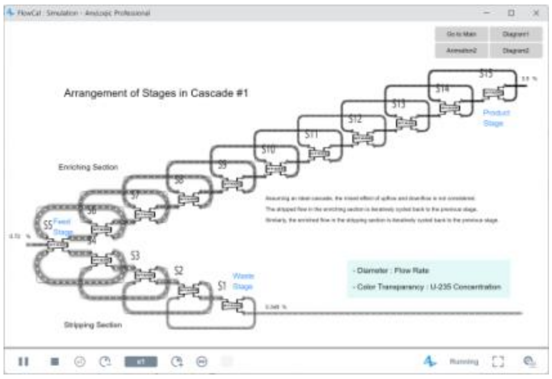


***Figure 2. Mass flow in cascade of single stage***

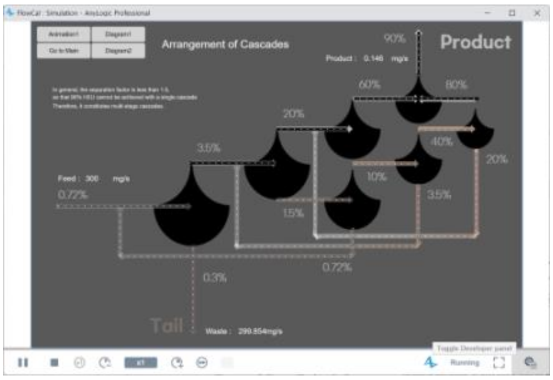


***Figure 3. Mass flow in the entire cascade***

The calculation results of the model for the production of 1 kg of 90 %-HEU are as follows.

- Required Feed: 555.55 kg
- Amount of Waste: 552.75 kg
- Generated intermediate products: 80 % HEU 1.80 kg (If the composition inside the cascade is not changed, intermediate products will inevitably occur)
- The required amount of separation work: 495 SWU/yr

The same cascade without considering intermediate products, the calculation result is as follows.

- Required Feed Amount: Approx. 4,800 kg
- Amount of Waste generated: Approx. 4,176 kg
- Intermediate products generated: Various intermediate products such as 1.5 %, 10 %, 40 % are remained
- The required amount of separation work: Approx. 3,155 SWU/yr

During a 2010 visit to Dr. Hecker, North Korea's segregation work was estimated at 8,000 SWU/yr, but it can be estimated at 16,000 SWU/yr by considering the capacity expansion later. [6] According to the above analysis results, when cascades are connected in multiple stages to recycle intermediate by-products, it is possible to produce about 32 kg/yr of 90 %-HEU, and if intermediate by-products are not considered, only 5 kg/yr of 90 %-HEU Only production is possible. Of course, since neither of the two analysis cases is a configuration that can utilize the efficiency of the centrifuge to the fullest, it is necessary to redesign the configuration of the optimized cascade to determine the correct nuclear capability and perform the calculation again on this.

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