

# Assessment of parameters of gas centrifuge and separation cascade basing on integral characteristics of separation plant



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## HIGHLIGHTS

- We developed the calculation method to assess a feed flow rate into a gas centrifuge.
- It is based on the knowledge of the integral characteristics of a separation plant.
- Our method is verified by comparison with the results of the independent one.
- The method also allows to specify other features of the separation cascade work.

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## ABSTRACT

A calculation technique to assess a feed flow rate into a single GC, a total number of centrifuges in a separation cascade and to determine its likely configurations basing on the known integral characteristics of a centrifugal plant is developed. Evaluation of characteristics of the industrial gas centrifuge TC-12 and separation cascades of the NEF plant performed by two independent calculation techniques demonstrates their satisfactory agreement. This methodology would help to some extent the nuclear inspectors in evaluating and assessing the capability of an enrichment facility, and discovering any use for undeclared purposes.

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## 1. Introduction

In recent years, a few papers have been published in which supposed geometrical and flow characteristics as well as the separative capacity of the URENCO and US uranium gas centrifuges (GCs) are discussed (Glaser, 2008; Kemp, 2009). However, any information on such important characteristic of these GCs as a feed flow rate is absent there. At the same time, the major characteristics of separation plants are known as they are submitted for approval to national supervisory authorities, giving permission for construction of a plant. The aim of this study is to develop a calculation procedure that would allow to estimate a feed flow rate into a single GC, a total number of GCs in a separation cascade and a possible cascade configuration (a distribution of flow and concentrations of a separating mixture over cascade stages) using only the data on the integral characteristics of a centrifugal plant. We believe that such assessments similarly to the papers (Carchon et al., 2011;

Migliorini and Wood, 2012) would allow the International Atomic Energy Agency (IAEA) inspectors to evaluate the performance of the GCs at an enrichment facility without the knowledge of technical details of a GC and to assess its actual operation status.

To demonstrate the possibilities of our calculation technique we carried out the analysis of likely cascade configurations and a single GC parameters using the legal information on the National Enrichment Facility (NEF) plant, being built in the Lee County, the State of New Mexico, USA by Enrichment Technology Company Limited (ETC), which is equally owned by the international consortium company URENCO and the French company Areva (Safety Analysis Report, 2004–2005).

In developing the method of calculation the information has been used regarding a scheme of separation stages connection in a centrifugal plant for uranium enrichment contained in the German patent (Zeller, 1987), which is supposed to be applied in the construction of the NEF plant. The main idea proposed in the patent is as follows. Connection of cascade stages provides the cross-links between them in a such manner that the depleted part of a feed flow from each stage (the so-called "tail") goes back merging with a feed flow at the entrance of a previous stage through a special device that equalize pressure of a working gas in piping. It allows to unite the feed lines of all stages in a cascade in one. The purpose of application of this cascade scheme is to achieve the possibility

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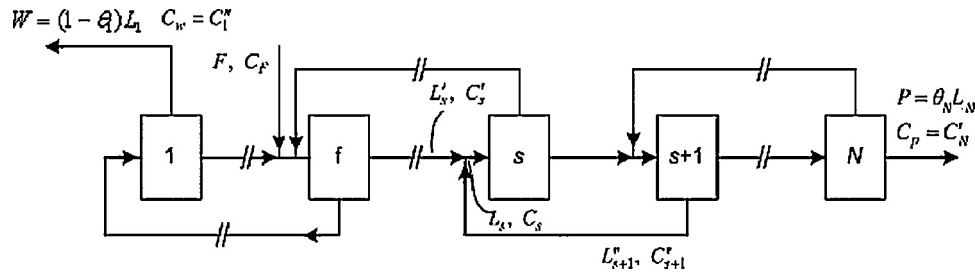


Fig. 1. Separation cascade scheme.

of deliberate variation of the  $^{235}\text{U}$  isotope content in the tails (tails assay) at its constant concentration in the product stream outgoing the cascade without reducing the separative performance of stages. Variation of a gas centrifuge cut is achieved due to backpressure provided by a special device. It leads to changing the concentration of a target component in the tails at a constant or slightly changing the separative capacity of a cascade as a whole.

## 2. Method of calculation

A schematic diagram of a countercurrent symmetric separation cascade usually used for uranium enrichment by GCs is shown in Fig. 1.

Here,  $s = 1, 2, \dots, N$  is a stage number in a cascade;  $f$  is a stage number in which a feed flow  $F$  with a concentration of a target component  $C_F$  enters a cascade;  $P$  and  $W$  are the product and waste flows from a cascade with the  $C_P$  and  $C_W$  concentrations of a target component, respectively;  $C_s$ ,  $C_s'$  and  $C_s''$  are the  $^{235}\text{U}$  concentrations in one ingoing ( $L_s$ ) and two outgoing (enriched  $L_s'$ ) and (depleted  $L_s''$ ) flows in a cascade stage with the  $s$ th number;  $\theta_s$  is a cut at the  $s$ th stage.

The construction application for the NEF plant (Safety Analysis Report, 2004–2005) says that it consists of three modules located in separate buildings. Each of them divided into two cascade halls and in turn each hall composed of 8 separation cascades. It is known that the maximum feed flow rate into the hall is equal to 187 kg/h, whereas its maximum separation capacity is 545,000 kgSWU/yr. The minimum feed flow rate into a single cascade is no less than 13.5 kg/h. The total separation capacity of the plant consisting of 6 halls is approximately 3.3 million kgSWU/yr. According to this application, the range of concentrations for the  $^{235}\text{U}$  isotope provided by the plant varies from 4 to the maximum of 5% (hereinafter used weight percents). The total efficiency of the plant following (Zeller, 1987) should be not less than 99%. While the tails assay may vary from 0.20 to 0.34%, with the average of 0.32% over the cascade. It is also known that the plant is equipped with centrifuge TC-12 which the separative power estimates as 40 kgSWU/yr (Glaser, 2008; Safety Analysis Report, 2004–2005).

In this study, it is assumed that the cascade is implemented by the classical scheme with inclusion of a feed flow into the first stage of the product section of a cascade. The ingoing flow to any cascade stage is formed by mixing the product flow from the previous stage and the tail one from the next cascade stage, if any.

In the case under consideration, the overall separation factor is considerably greater than unity. It does not allow to simplify calculation by applying the approximation on low enrichments at cascade stages.

The following parameters are considered as known during calculation:

- the total feed flow rate  $F$  to the cascade and the target component concentration  $C_F$  which is taken as the concentration of the  $^{235}\text{U}$  isotope in the natural uranium isotope mixture;

- the separative performance of a single GC  $\delta U$  and the total separative power of the cascade  $\Delta U$ ;
- the value of a stage cut  $\theta$  is taken identical for all stages;
- the total number of stages  $N$  in the cascade;
- the number of a stage  $f$  where the feed flow enters the cascade.

It should be mentioned that we do our calculation under conditions of strong uncertainty. It means that the actual values of  $\theta$ ,  $N$ , and  $f$  for the NEF plant as well as the exact value of the separative power  $\delta U$  are unknown for us. However, with sufficient level of accuracy one may assume that the total number of stages in a cascade does not exceed 20, and the number of stages in its enriching section is no more than 10 (Delbeke, 2009).

The purpose of the calculation procedure is to find in the first step the distributions of the  $L_s$ ,  $L_s'$ ,  $L_s''$  flows and the respective concentrations of a target component  $C_s$ ,  $C_s'$ ,  $C_s''$  over cascade stages. In the second step, the calculation of cascade efficiency  $\eta$  is carried out by the following formulas:

$$U_{\text{was}} = \sum_{s=2}^{N-1} [L_{s+1}'' V(C_{s+1}'') + L_{s-1}' V(C_{s-1}') - L_s V(C_s)] \quad (1)$$

$$\eta = \frac{\Delta U - U_{\text{was}}}{\Delta U} \quad (2)$$

where  $\Delta U$  is the separative power of a cascade;  $U_{\text{was}}$  is the lost enrichment power because of mixing the flows with non-equal target component concentrations in the ingoing flows at the entrance of cascade stages;  $V(C) = (2C - 1) \ln[C/(1 - C)]$  is the value function determining the value of 1 mol of a binary isotope mixture with a corresponding concentrations of a target component  $C_s$ ,  $C_s'$ , and  $C_s''$  in these flows (Cohen, 1951).

Calculation of flows in the enriching section of a cascade is carried out from stage to stage from the stage where the feed flow enters to a cascade to the rightmost stage with the  $N$  number. The values of all flows are calculated in terms of  $P$ , and the value of  $P$  is set equal to 1. The following relations can be determined from the equation of material balance at each cascade stage:  $L_s = (L_s'/\theta)$ ,  $L_s'' = ((1 - \theta)/\theta) L_s'$ . The product flow from the previous stage will be calculated by the obvious equation  $L_{s-1}' = L_s - L_{s+1}''$ . The procedure of calculation is performed until it reaches the stage with a number  $s = f + 1$  and ends by definition of product flow  $L_f'$ . Similarly, it is calculated the flow over cascade stages from left to right in the stripping section of the cascade by the formulas

$$\begin{cases} L_s' = \frac{\theta}{1 - \theta} L_s'', & L_1' = 1 \\ L_s = \frac{L_s''}{1 - \theta} & s = 1, \dots, f - 1 \\ L_{s+1}'' = L_s - L_{s-1}' \end{cases} \quad (3)$$

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