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presented by E.W. Becker

In the course of the past 10 years we have developed a process for enriching U^{235} which is based on pressure diffusion in supersonic jets[1]. The principle of the arrangement as used in the present state of development can be understood from Fig. 1; it shows a cut through the separation nozzle system. Its extension at right angles to the plane is arbitrarily adjustable. A mixture of about 5 mole% UF_6 and 95 mole% He is expanded through a slit-shaped nozzle. The bandshaped supersonic jet is deflected through 180° by a curved wall and subsequently divided, by means of a knife edge, into two fractions which are pumped off separately. The deflection of the jet by the curved wall results in a partial spatial separation of the components, the gas moving close to the deflecting wall becoming enriched in U^{238}, while U^{235} accumulates in the remaining fraction. The helium admixture increases the velocity of UF_6, thereby improving the separation effect.

The optimal inlet pressure of the feed gas is inversely proportional to the characteristic dimensions of the separation nozzle system, e.g. the width of the nozzle slit. As high inlet pressure is desirable for economic reasons, inexpensive mass-fabrication of nozzle systems with small characteristic dimensions is a key problem of the separation nozzle process.

Fig. 2 shows the cross section of a separation nozzle system currently in use. The diameter of the deflecting groove is 0.2 mm, the width of the nozzle slit is 0.03 mm.

In the upper left corner of Fig. 3, the elementary separation effect, ε_A, of the uranium isotopes obtained with the system shown in Fig. 2 is plotted against the inlet pressure, p_o, of the UF_6/He mixture. A maximum value of ε_A = 1,3 % occurs at 600 mm Hg. The lower left corner of Fig. 3 shows the pressure dependence of the so-called UF_6-cut. In the case under consideration the cut corresponding to the maximum of ε_A turns out to be 17 %.

The right side of Fig. 3 shows the elementary separation effect and the UF_6-cut depending on the expansion ratio, p_o/p_M. With an expansion ratio of 8, ε_A is as high as 2 %. In practical applications, however, a lower value of the expansion ratio and a correspondingly lower value of the elementary separation effect is optimal.

When multiplying the elementary separation effect in a cascade system the UF_6-cut, ϑ_{UF_6}, has to be fixed according to the well known non-mixing condition. For the separation nozzle process a UF_6-cut of 1/3 seems to be optimal. This corresponds to a cascade in which the light fraction of each stage is fed to the stage two stages above. Table 1 summarizes the working conditions and the results for ϑ_{UF_6} = 1/3, considered as present standard.

Diameter of deflecting groove (mm)	0.2
Width of nozzle at throat (mm)	0.03
Inlet pressure, p_o, (mm Hg)	600
Internal expansion ratio p_o/p_M	4
UF_6-cut, ϑ_{UF_6}	1/3
Element. separ. effect, $\varepsilon_A.10^2$	1.18
UF_6-throughput, $\frac{\text{g-mole } UF_6/h}{\text{m slit length}}$	27

Table 1: Working conditions and results for ϑ_{UF_6} = 1/3.

At present, in cooperation with industry, we are developing the technical and economical details of a demonstration plant on the basis of the data given in Table 1. The purpose of this study is to aid in the evaluation of the economic aspects of the separation nozzle process. It should be emphasized that there are at present no definite plans for the construction of such a plant.
Fig. 4 shows the general scheme of the plant. The product and waste concentrations are fixed to 3.0 and 0.25 % U^{235}, respectively. Two stage centrifugal blowers with intermediate and final cooling are provided for the recompression of the gas. Assuming that an internal recompression of 25 % may be accomplished inside the separating elements by properly utilizing the kinetic energy of the jet, the compression ratio of the blowers was assumed to be 3. As the highest partial pressure of UF_6 in the separation stages is only 30 mm Hg, no condensation problems would occur when working at room temperature. However, to ensure an economic operation of the cooling towers, the suction temperature was raised to 35°C. Suction capacities of $1 \cdot 10^5$ m^3/h and $3{,}4 \cdot 10^4$ m^3/h are assigned for the basic and the smaller stages, respectively. The isothermal efficiency of the blowers including motor drive was assumed to be 70 %. The plant consists of 335 large and 235 small stages. With a cascade efficiency of 95 % and 90 % on-stream time, the annual net separative work capacity of the plant would be 600,000 kgU (i.e. 600,000 SWU). This corresponds to about 1/10 of the published figure for the capacity of one American diffusion plant[2]. The net output of the demonstration plant would be $158 \cdot 10^3$ kg uranium per year with 3 % U^{235}. It would need $920 \cdot 10^3$ kg of natural uranium per year as feed.

One of the larger stages of the plant under consideration is being constructed by industry. The stage will be ready for testing at the end of the next year. It will contain 100 tube-shaped separating elements 2 m in length. One of these tubes is shown schematically in Fig. 5. Each tube has ten separating slits on its circumference. The slits are fed with the He/UF_6 mixture via half the gas channels inside the tube. The rest of the channels leads off the heavy

fractions, while the light fractions enter into the casing surrounding the separating elements. Fig. 6 shows a section of a laboratory type tube employing 4 separating slits. It works with full efficiency at an inlet pressure of 160 mm Hg.

Fig. 7 gives a schematic representation of the separating stage as a whole. The tank containing the 100 separating elements has a diameter of 2 m. It is connected with the compressor and its integrated cooling system via an intermediate section. In this section the feed gas is distributed to the separating elements and the recompressed gas is led off to the next stage.

At the top of the tank the heavy fractions of the separating elements are collected to be fed to the preceding stage. At the same time the heavy fraction coming from a higher stage is introduced into the tank to be mixed with the light fraction coming from the separating elements.

As a consequence of the high sonic velocity of the He/UF_6-mixture, the compressor and its motor drive can be kept relatively small and thus are easily integrated into the separating stage. As a whole, the stage appears as an upright cylindrical unit, 7 m in total height. Its expected output is 1700 SWU/year. For mass production the price of the large stage, including piping and assembly, was precalculated to be $ 95,000. The price of the smaller stage, one third the size of the large stage, was assumed to be one half of this sum. The following estimation of the total investment costs of the demonstration plant can therefore be made (Table2).

335 large stages	32 Million $
235 small stages	11 " "
External cooling system	4 " "
He recovery and UF_6 purification	3 " "
Energy distribution and instrumentation	9 " "
Plant building incl. basement, space for support facilities, and utilities, 70 x 200 m^2, total height basement to roof 14 m; (75 $/$m^3$)	15 " "
Total investment incl. assembly	74 Million $

Table 2: Estimation of the investment costs of the demonstration plant (excluding power station).

With a net output of 600,000 SWU/a, the specific investment of the separation nozzle demonstration plant turns out to be

123 $/SWU/a

This value corresponds within the limit of error to the value published for the American diffusion plants which are ten times larger. According to the studies of Fréjacques and Galley[3], as well as of Mårtensson[4], the investment costs of a diffusion plant with the capacity of the projected separation nozzle demonstration plant would be higher by at least a factor three.

Table 3 shows the electric power requirements:

335 large stages at 1.22 MW	=	408	MW
235 small stages at 0.41 MW	=	97	MW
Auxiliary equipment	=	15	MW
Total net output of the required power station	=	520	MW

Table: 3: Electric power requirements of the demonstration plant.

The corresponding specific energy consumption of

6850 kwh/SWU

turns out to be still higher by a factor of 2.2 as compared with the corresponding published figure for the American plants working under full load[2]. To meet the specific energy consumption of the diffusion process, the elementary separation effect of the nozzle process has to be raised by a factor of 1.5, which appears to be within the range of physical possibilities.

A separation nozzle plant is expected to have an equilibrium time about 100 times smaller than that of a comparable diffusion plant mainly as a consequence of the higher elementary separation effect and the higher sonic velocity of the process gas. This offers the possibility of temporarily shutting down the operation without loss, thereby providing a means to affect favourably the power costs.

In addition the smaller number of separation stages and the avoidance of porous membranes should result in lower personnel and maintenance costs. Since relatively low specific investment costs can be attained with relatively small plants, the separative work capacity can be economically adapted to growing needs.

In conclusion, we believe that the separation nozzle process holds considerable promise to become an alternative to the classical diffusion process. A deeper understanding of the separation mechanism will undoubtedly result in further economic improvements.

References

1) A summary of our previous work in this field is given in: Separation of the Isotopes of Uranium by the Separation Nozzle Process, E.W. Becker, K. Bier, W. Bier, R. Schütte, D. Seidel. Angew. Chemie International Edition (in English) 6, No 6, 507-518 (1967). A description of a ten stage pilot plant will be given in the next paper. See also: Entmischung der Uranisotope in einer zehnstufigen Trenndüsenversuchsanlage, E.W. Becker, G. Frey, R. Schütte, D. Seidel, Atomwirtschaft, 13, Nr. 7, 359-362 (1968).

2) USAEC Release No K-145, June 14, 1967. See also: USAEC Gaseous Diffusion Plant Operations, ORO-658, Febr. 1968.

3) C. Fréjacques, R. Galley, 3. U.N. Intern. Conf. Peaceful Uses of Atomic Energy, Geneva 1964, Paper 28/P/89.

4) M. Mårtensson, I.A.E.A. Symp. Economics of Nuclear Fuels, Gottwaldov (1968), Paper SM-105/21.

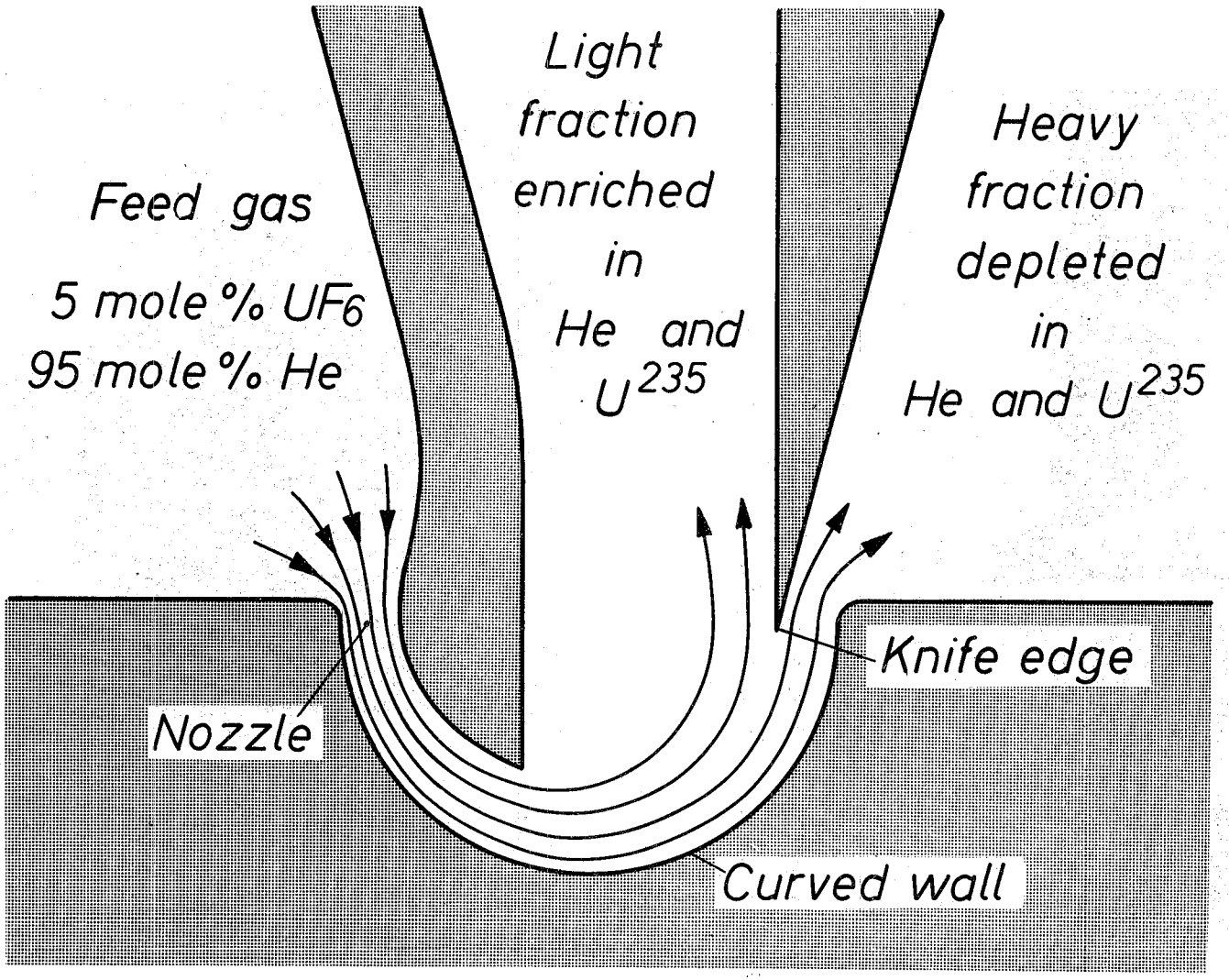


Fig. 1: Cross section of the separation nozzle arrangement with a schematic representation of the streamlines.

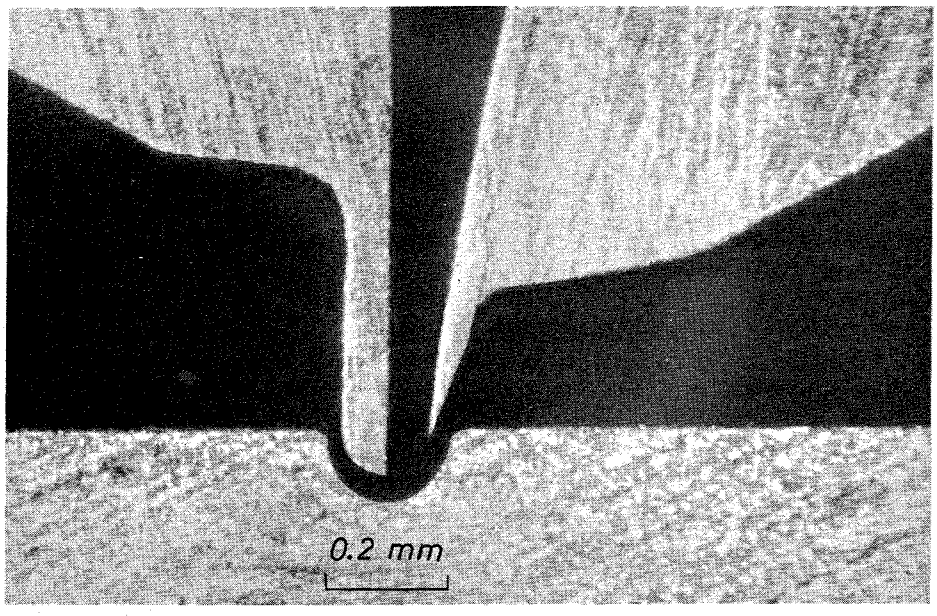


Fig. 2: Photograph of the separation nozzle system as used for experiments shown in Fig. 3.

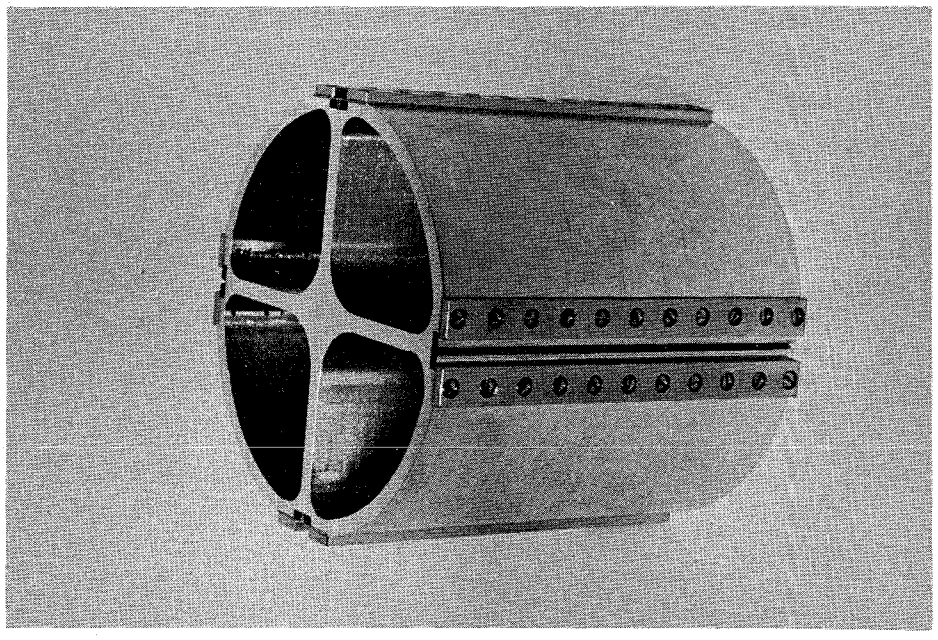
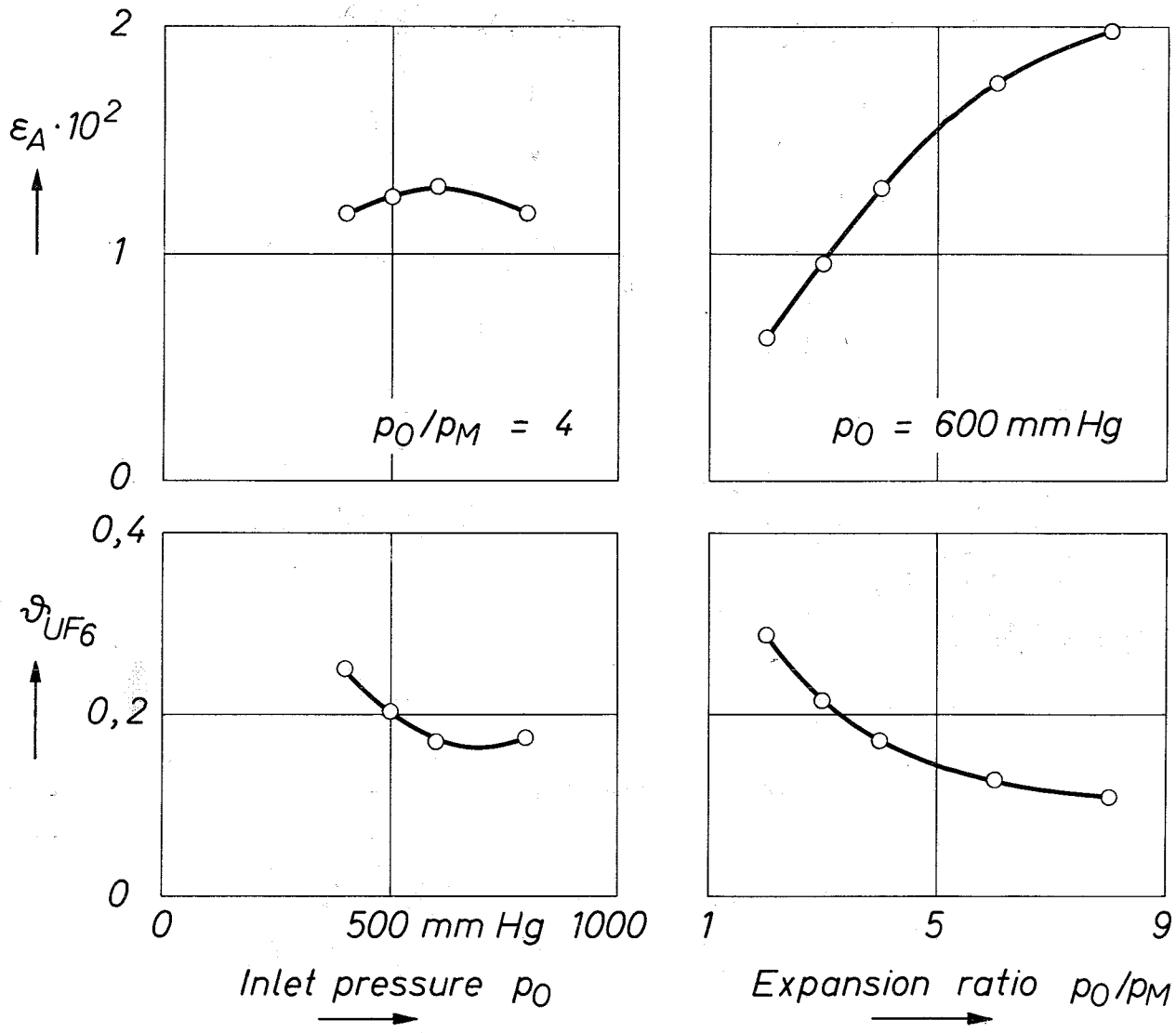


Fig. 6: Laboratory type separating element with 4 separating slits.

$$\varepsilon_A = \frac{n_M\,(1 - n_K)}{n_K\,(1 - n_M)} - 1$$

n_M, n_K = mole fractions of the light uranium isotope in the light and heavy fractions of UF_6



$$\vartheta_{UF6} = \frac{\text{flow rate of } UF_6 \text{ in the light fraction}}{\text{flow rate of } UF_6 \text{ in the feed gas}}$$

Fig. 3: Effect of the inlet pressure p_o and of the expansion ratio p_o/p_M on the elementary separation effect ε_A and on the cut of the UF_6-gas, ϑ_{UF_6}.
Separation system as shown in Fig. 2; He/UF_6-mixture containing 5 mole % UF_6.

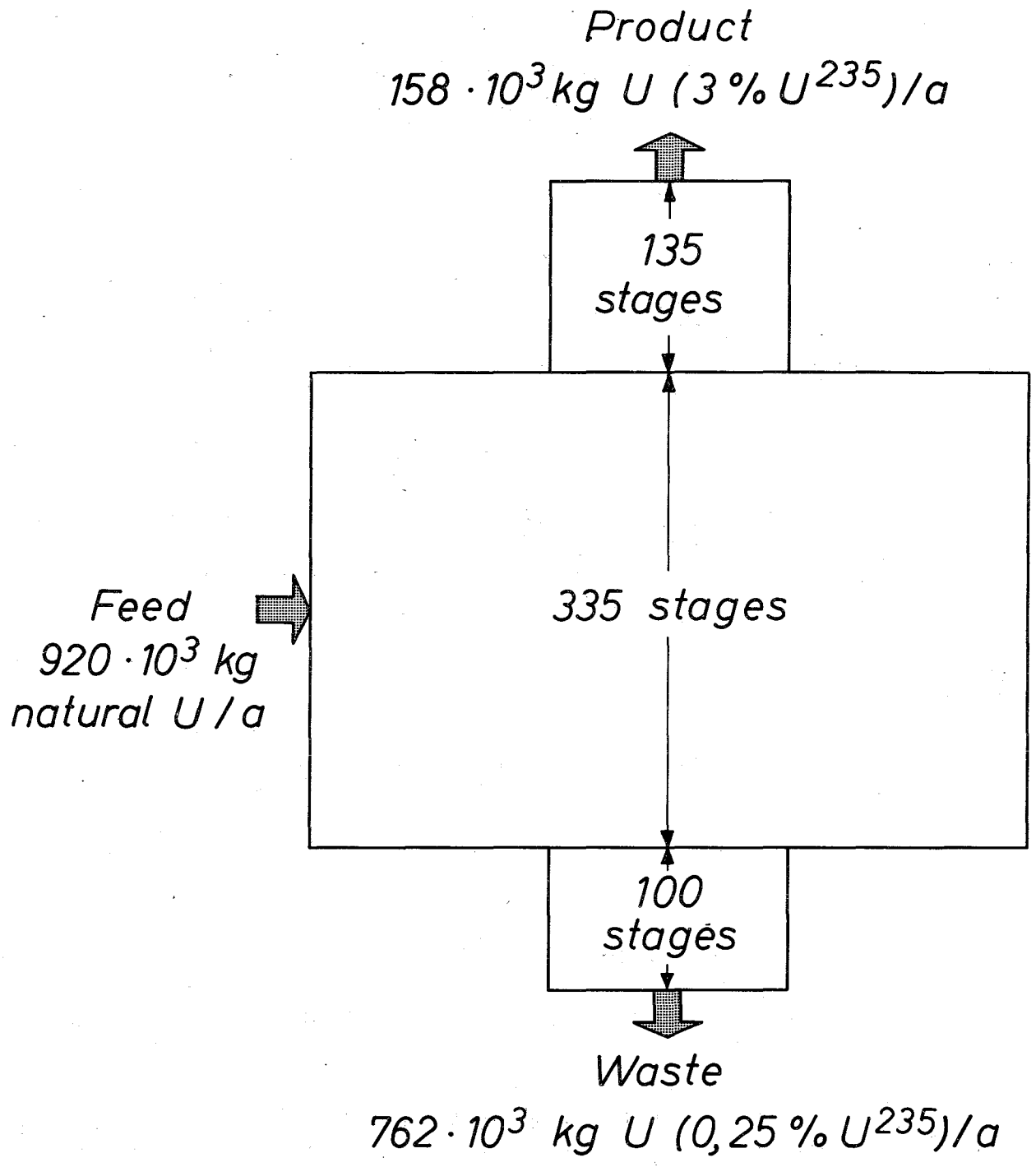


Fig. 4: General scheme of the demonstration plant under consideration.

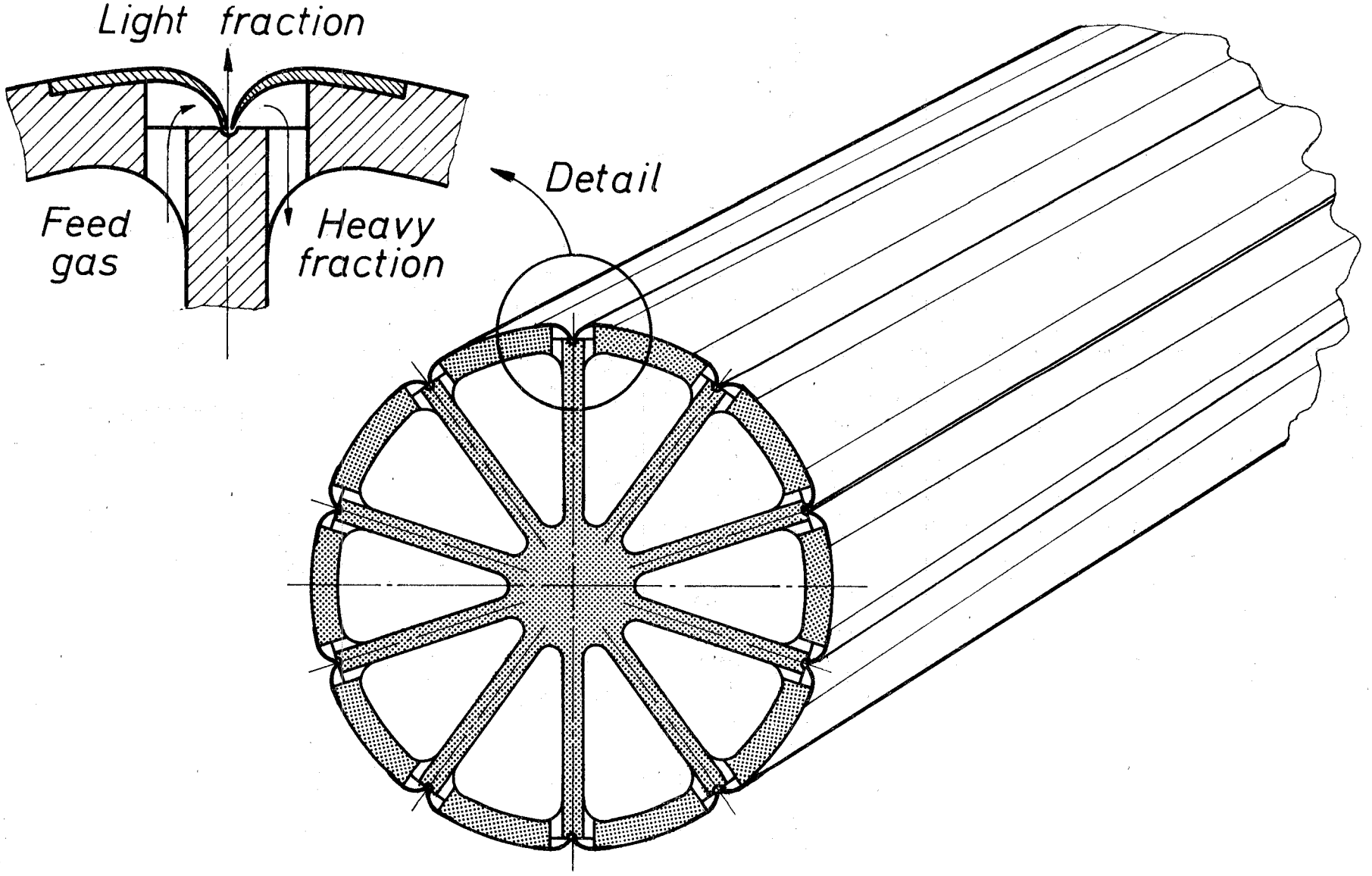


Fig. 5: Principle of a technical separating element with 10 separating slits.

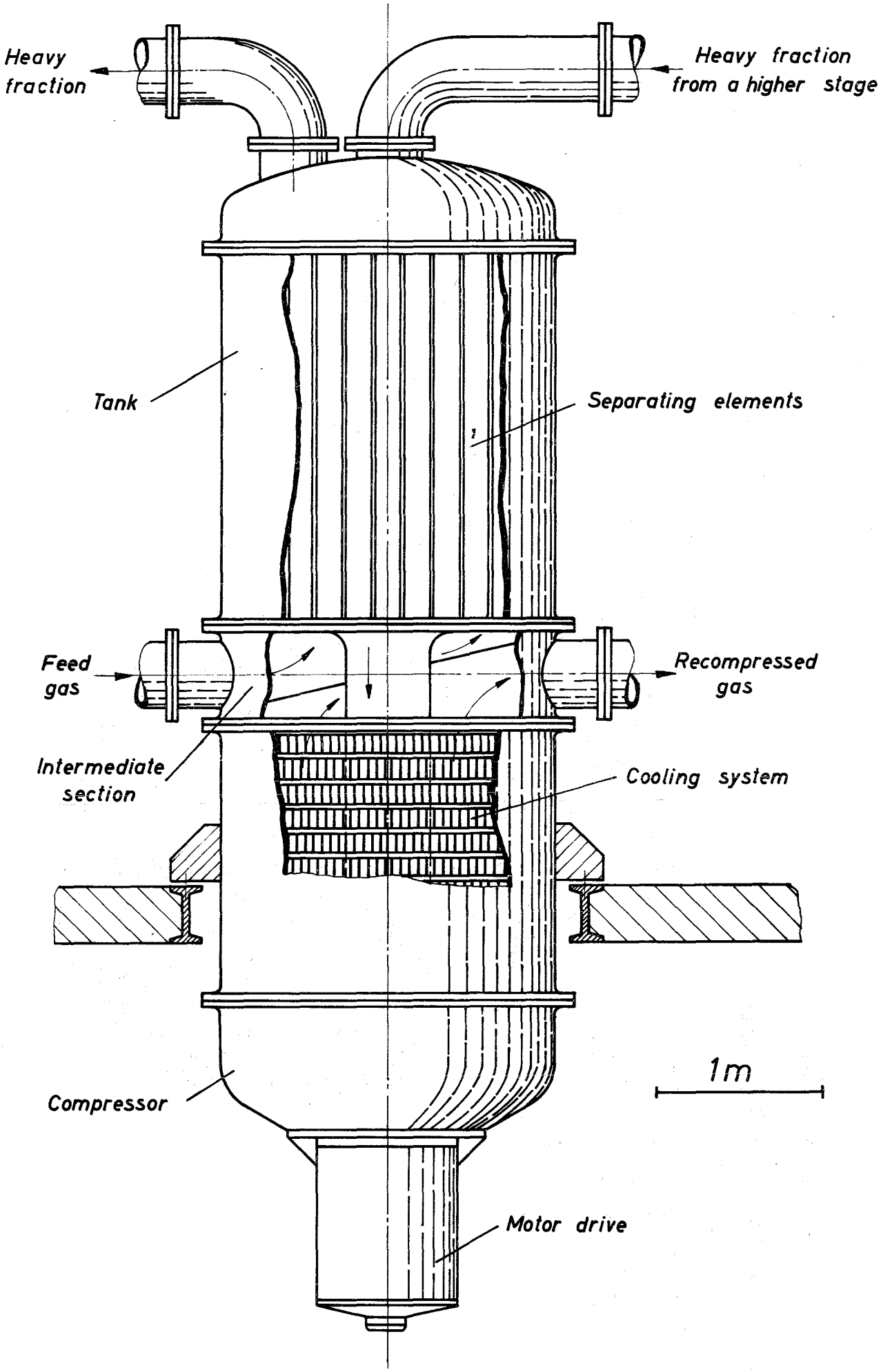


Fig. 7: Scheme of a complete separating stage of the demonstration plant under consideration.