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DEVELOPMENT AND TECHNICAL IMPLEMENTATION OF THE SEPARATION NOZZLE PROCESS FOR ENRICHMENT OF URANIUM-235

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Summary

The separation nozzle process developed by the Karlsruhe Nuclear Research Center relies on the centrifugal force in a curved jet consisting of uranium hexafluoride and a light auxiliary gas. It is applied on a technical scale in Brazil. There a cascade section consisting of 24 separation stages is being constructed which will be extended in two steps into a demonstration plant with a capacity of roughly 300 000 SWU/year. To produce separation nozzle systems with extremely small characteristic dimensions permitting plant operation at atmospheric pressure, a manufacturing process is being developed which relies on combined X-ray lithography and microgalvanic deposition (LIGA-technology). By applying this technology the prototype separation stages being constructed at the Karlsruhe Nuclear Research Center allow to realize commercial separation nozzle plants with capacities between one and four million SWU/year. Less than 300 separation stages are required to cascades with a product assay of 3.2% and a tails assay of 0.25% ^{235}U. A cost evaluation is given for such plants.

Entwicklung und technische Einführung des Trenndüsenverfahrens zur Anreicherung von Uran-235

Zusammenfassung

Das vom Kernforschungszentrum Karlsruhe entwickelte Trenndüsenverfahren beruht auf der Zentrifugalkraft in einem gekrümmten Strahl aus Uranhexafluorid und einem leichten Zusatzgas. Das Verfahren wird in Brasilien im technischen Maßstab angewendet. Dort ist ein aus 24 Trenndüsenstufen bestehender Kaskadenabschnitt im Bau, der in 2 Schritten zu einer Demonstrationsanlage mit einer Leistung von rund 300 000 kg UTA/Jahr ausgebaut wird. Für die Herstellung von Trenndüsensystemen mit extrem kleinen charakteristischen Abmessungen, die einen Anlagenbetrieb bei Atmosphärendruck ermöglichen, wird ein auf der Kombination von Röntgenlithographie und Mikrogalvanik beruhendes Verfahren entwickelt ("LIGA-Technologie"). Mit den in Karlsruhe in der Erprobung bzw. im Bau befindlichen Prototyp-Trennstufen lassen sich bei Einsatz der LIGA-Technologie kommerzielle Trenndüsenanlagen mit Leistungen von 1 Mio bis 4 Mio kg UTA/Jahr realisieren, bei denen Produkt- und Abfallkonzentrationen von 3,2 bzw. 0,25% ^{235}U mit weniger als 300 Trennstufen erreicht werden. Es wird eine Kostenanalyse für solche Anlagen mitgeteilt.

Contents

1. Introduction

The separation nozzle process developed by the Karlsruhe Nuclear Research Center relies on the centrifugal force in a curved jet consisting of uranium hexafluoride and a light auxiliary gas /1/. Its relatively high stage separation factor in combination with a high stage throughput permits construction of commercial enrichment plants with attractively low specific investment costs. An economically favorable production of enriched uranium is assured in particular, if low-cost electrical power is available.

Since 1970 the STEAG company, Essen, has participated in making the separation nozzle process mature for industrial application. In 1975 Brazil decided in favor of the separation nozzle process to become the technology for enriching its uranium resources. Since a considerable demand for nuclear fuel is not to be expected until the end of this decade, it was decided to implement the process in Brazil by construction of a relatively small demonstration plant and, in parallel, to further advance by joint efforts separation nozzle technology for commercial application. The Brazilian partner in this collaboration is NUCLEBRAS /2/. On the German side, INTERATOM, Bensberg, is a partner besides the Karlsruhe Nuclear Research Center and the STEAG company.

Since 1979 a so-called First Cascade consisting of 24 separation nozzle stages has been under construction in Brazil. Extension into the demonstration plant will take place in two steps which are termed Demo 1 and Demo 2. For Demo 1 a technology frozen in late 1980 is used which differs from the technology of the First Cascade by its operating pressure increased by the factor 2 and by its specific energy consumption reduced by about 15%. Demo 1 will be capable of supplying fuel to one 1000 MW power station, beginning in 1986.

It is intended to test by Demo 2 the advanced technology for commercial plants and to increase the production capacity to about 300 000 SWU/year. *)

In parallel to work for the demonstration plant carried out in Brazil, two prototypes of larger scale separation nozzle stages are being tested in Karlsruhe with a view to construct commercial plants.

In the following chapters the technical implementation and the further development of the separation nozzle method will be described. Particular emphasis will be laid on the description of the advanced separation nozzle technology to be applied in commercial plants. In addition, a detailed cost evaluation will be given for such plants.

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*) According to earlier plans /2/ the technology for the demonstration plant was not to be frozen before 1982 and the extension was to be realized with a uniform technology. Due to the modified strategy the date for the first production of reactor-grade material has been advanced and, at the same time, the possibility provided to test an improved technology in the second extension step.

2. First Cascade

Figure 1 shows the principle of the separation nozzle system with single jet deflection used in the First Cascade: A mixture of gaseous uranium hexafluoride and hydrogen flows along a curved wall at a high velocity. At the end of deflection the gas jet is split up by a knife into a light fraction and a heavy fraction which are withdrawn separately. The hydrogen added improves considerably the separation of the uranium isotopes; this is due mainly to the increase in flow velocity of the mixture, associated with the reduction in the mean molecular weight. To be able to apply the highest possible gas pressure, one selects the characteristic dimensions of the separation nozzle system so that they are as small as possible.

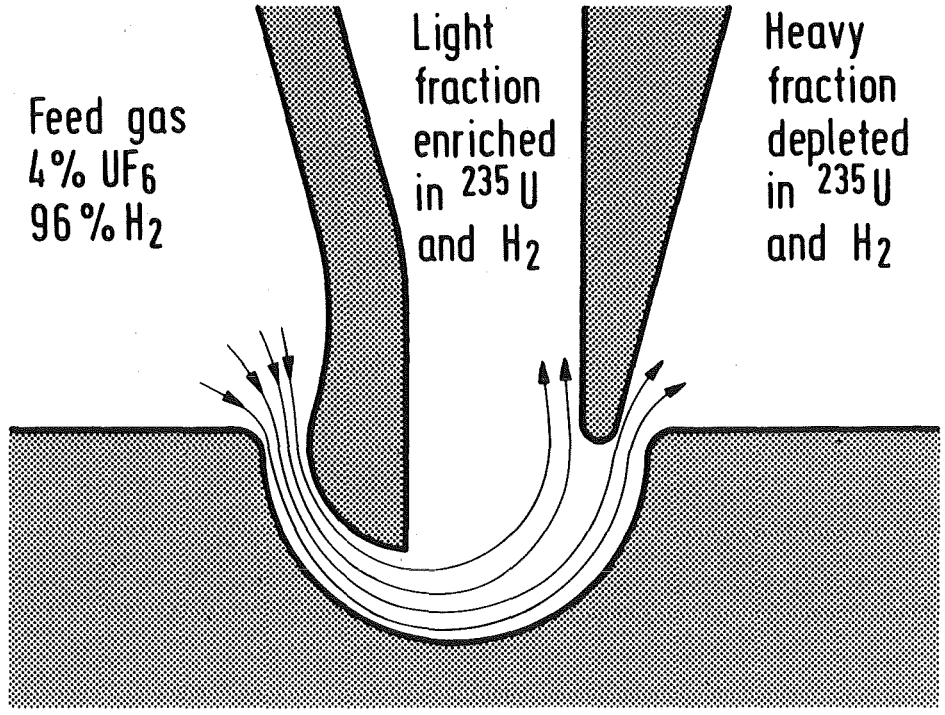


Fig. 1: Principle of the separation nozzle system with single jet deflection used in the First Cascade.

The separation nozzle systems of the First Cascade have a radius of the deflection groove of 100 µm. They are fabricated by two methods jointly developed with industry: The first employs purely mechanical means (Messerschmitt Bölkow Blohm, Munich), the second relies on stacking photo-etched metal foils (Siemens AG, Munich) (Fig.2). In the First Cascade separation elements produced under both methods are used.

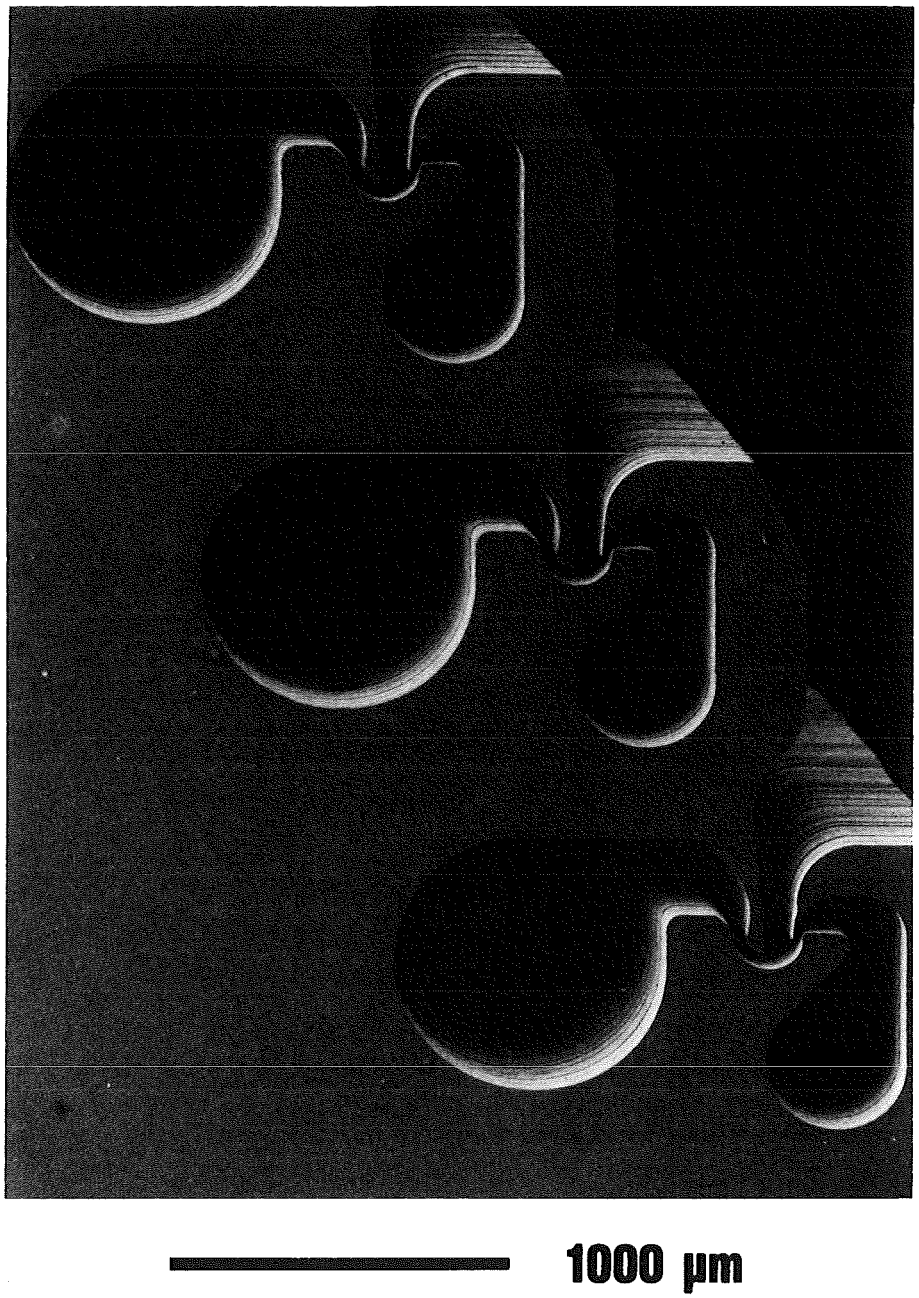


Fig.2: Segment of a technical scale separation nozzle element produced by stacking photo-etched metal foils, with single jet deflection. Three of the many separation nozzle systems arranged side by side with the related gas distribution channels can be recognized. The radius of curvature of the deflection groove is 100 µm.

The separation nozzle systems are installed in gas distribution tubes. Quite a number of such separation element tubes are operated in parallel in a tank which, together with a radial compressor and a cooler, makes up one separation nozzle stage. Figure 3 shows the prototype of the separation nozzle stages used in the First Cascade with a compressor suction capacity of 33 000 m^3/h (SR 33).

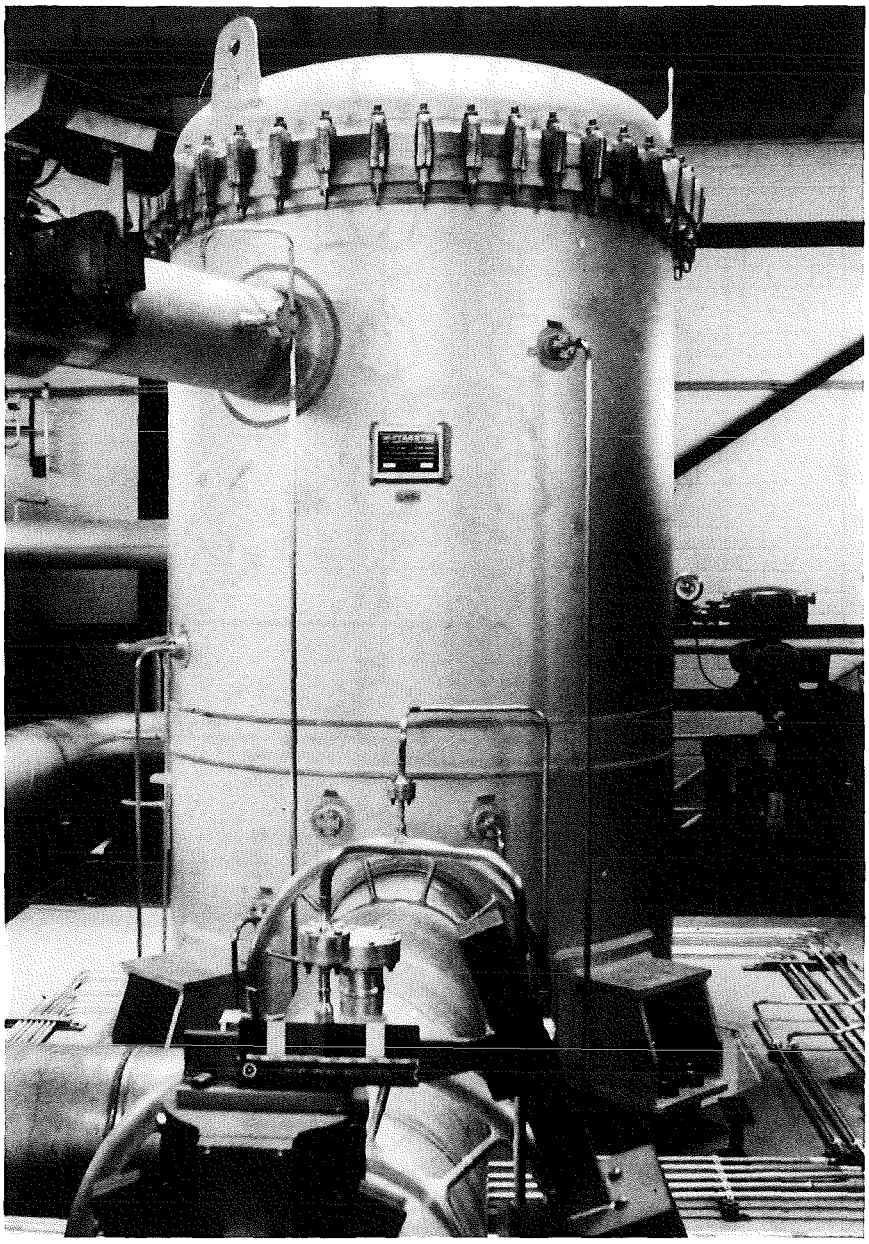


Fig.3: Prototype of the separation nozzle stage SR 33 with a compressor suction capacity of 33 000 m^3/h. The diameter of the stage is 1.5 m.

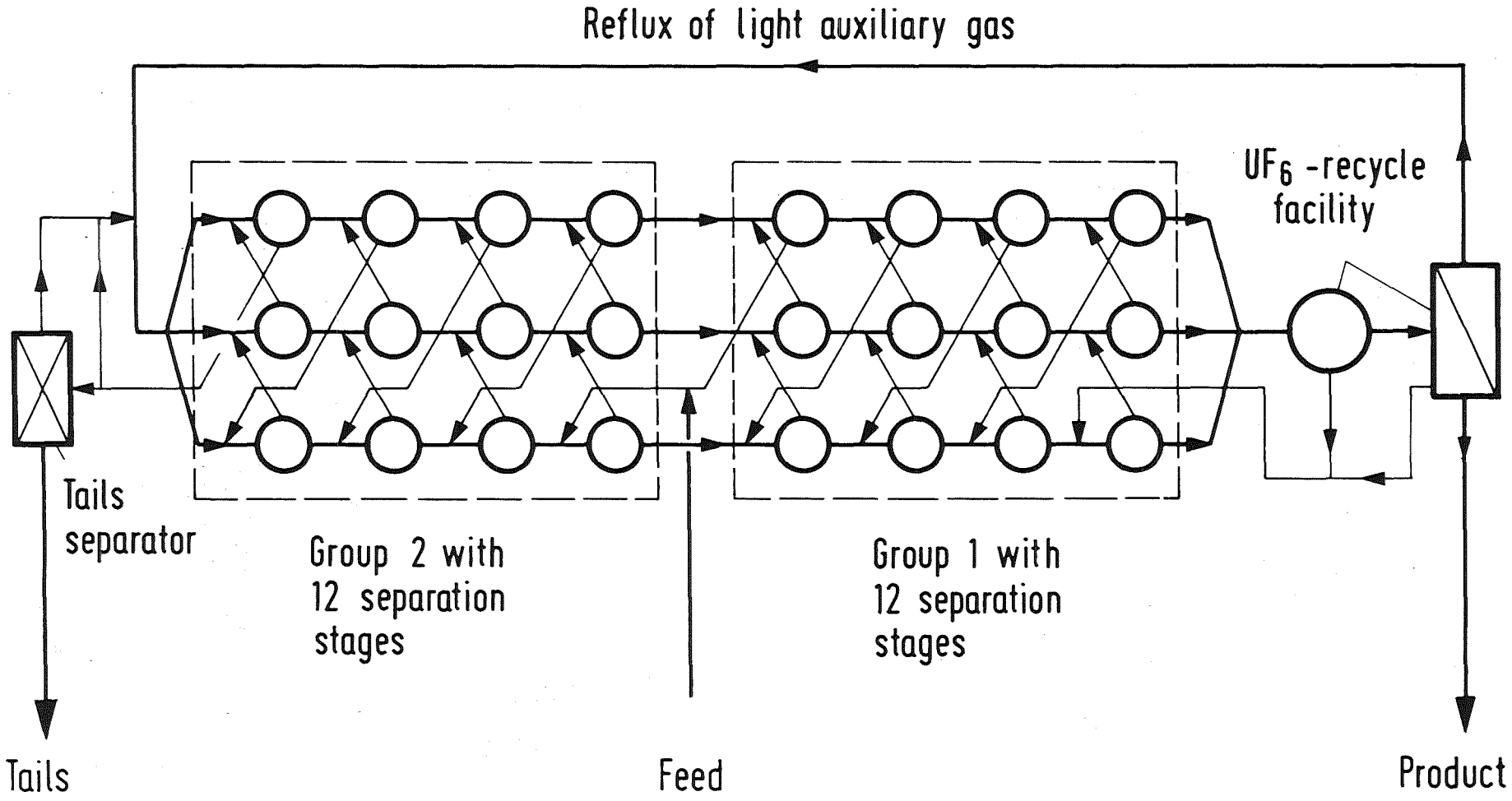


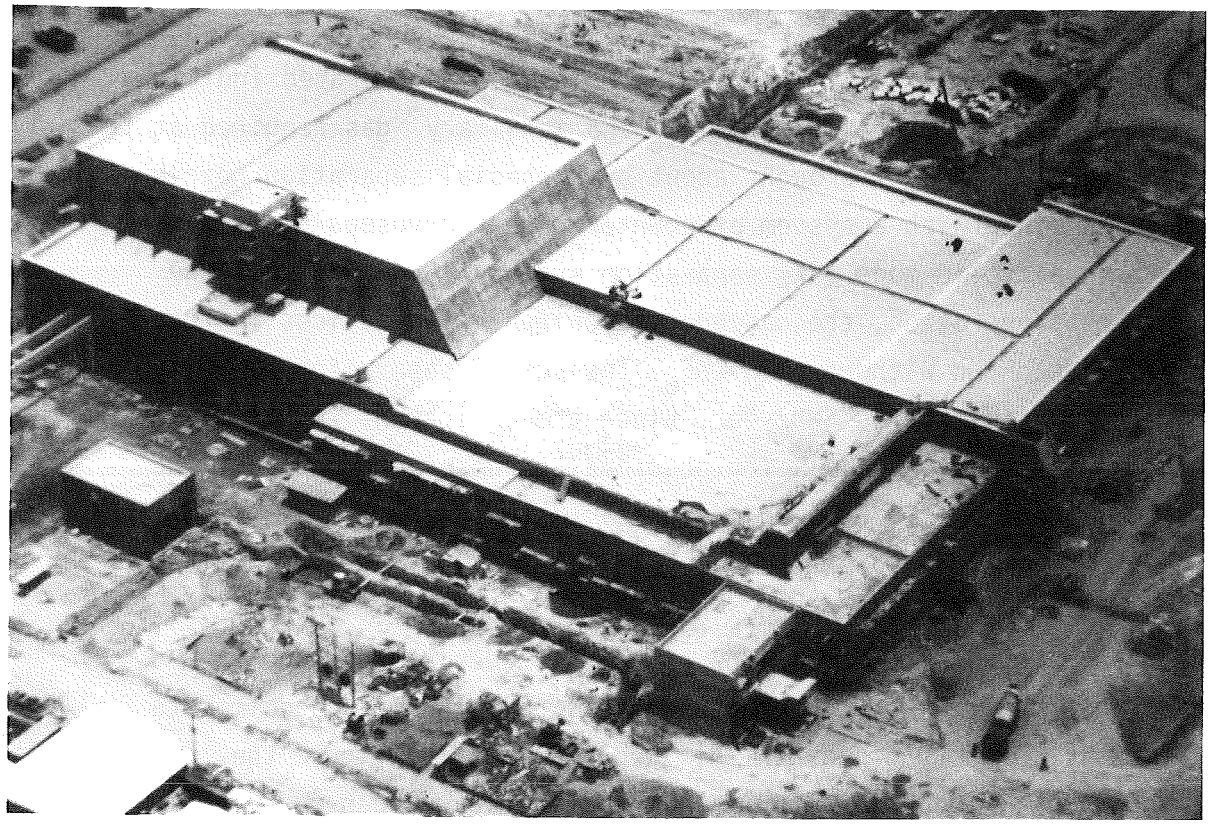
Fig.4: Flowsheet of First Cascade.

In Fig.4 the flowsheet of the First Cascade has been represented; the 24 stages are arranged in two groups which can be operated individually or in series. The separation of UF_6 and auxiliary gas required at the top of the cascade is brought about by a special separation nozzle stage combined with a system of countercurrent cryoseparators operating in a cyclic mode (UF_6 separation system) /3,4/. To test the enrichment operation, the cascade is equipped with devices for controlled feed and withdrawal of UF_6. The sum of separation capacities of the stages is 6 000 SWU/year. Since the enrichment factor of the First Cascade is too small for practical purposes, the product and waste streams are recombined in normal test runs.

Figure 5 shows the central building of the demonstration plant at Resende, a town situated on the highway between Rio de Janeiro and Sao Paulo. Besides the First Cascade this building will accommodate the basic infrastructure. In the lower part of the figure the two concrete foundations for the separation stages can be recognized. The start of operation of the First Cascade is scheduled for early 1984.

3. Demonstration Plant

In the first section of the demonstration plant (Demo 1) the type of separation element, the stage size and the stage assembly of the First Cascade will be retained (Figs. 1-3). By reducing the critical sizes of the separation nozzle systems to half their previous values and by improving their geometric fine structures, it was possible to bring up the separation capacity of the stages to more than double their value. At the same time, the specific energy consumption was decreased by about 15%.



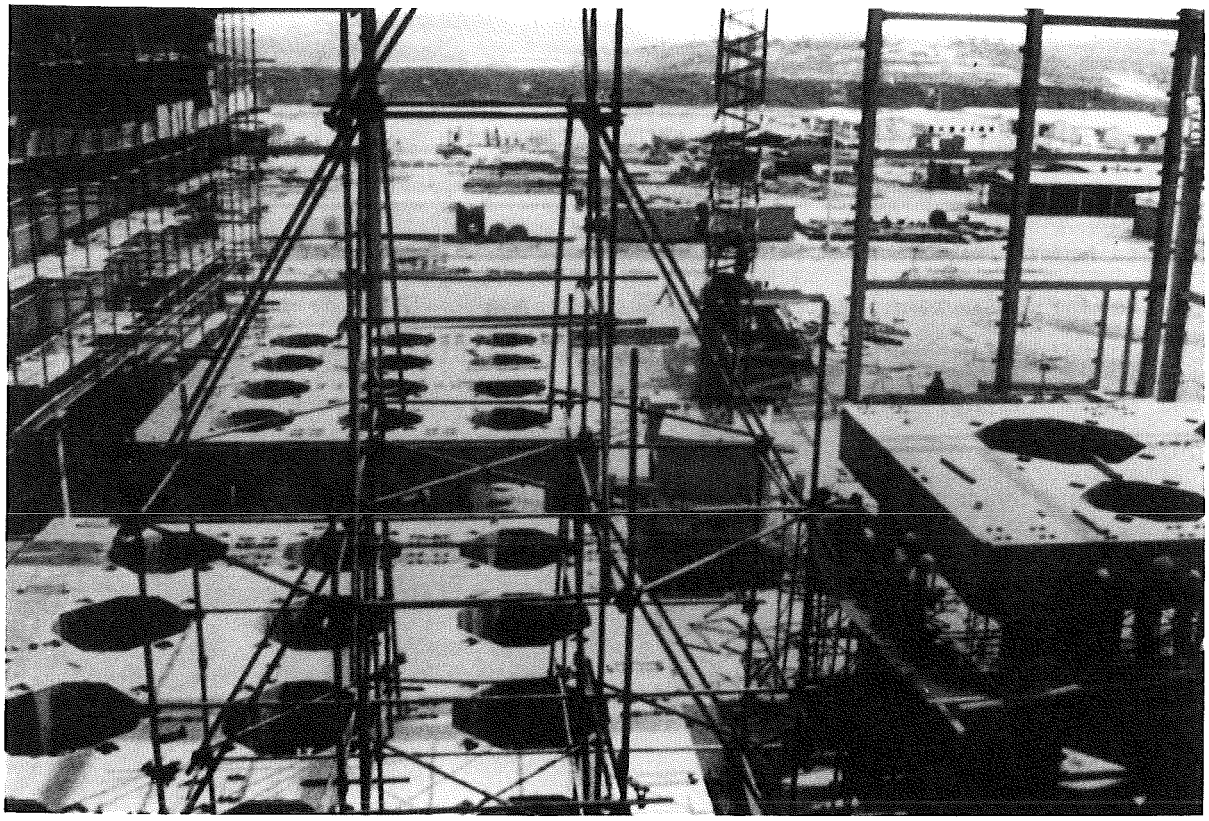


Fig.5: Central building of the Demonstration Plant accommodating the First Cascade and the basic infrastructure at Resende (Brazil). In the lower photograph the concrete foundations for the separation stages can be seen.

The separation nozzle systems with a mean deflection radius of 50 µm are fabricated according to the same methods as those in the First Cascade. On account of the greater susceptibility of small systems to getting polluted, the separation stages are equipped with a metal filter immediately preceding the separation elements; its relative pressure drop is less than 2%. Figure 6 shows the result of testing a separation stage of the type to be used in Demo 1 with 50 µm separation elements supplied by Messerschmitt Bölkow Blohm. The elementary effect of uranium isotope separation, ε_A, amounting to about 1.7%, and the uranium cut, θ_U, amounting to about 18%, had been measured over a period of 2000 hours of operation. In cascade operation, the uranium cut is set to its nominal value of 25% by means of the control valves installed in the heavy fraction ducts.

It can be noted that during the 2000 hours of testing no variation of the stage characteristics is observed. Based on this result and on further long-duration tests performed over 30 000 hours in test loops equipped with technical-scale separation element sections, it can be assumed that the separation stages of Demo 1 will retain their separative capacity during several years of permanent operation.

Demo 1 will be equipped with 264 identical separation stages. Together with the separation stages of the First Cascade, the sum of the separative capacities of all stages amounts to 135 000 SWU/year. Since the stages of Demo 1 will be arranged as a square cascade which must be operated at a relatively low withdrawal rate in order to produce reactor-grade material, the cascade efficiency will attain only 62%. Consequently, the net separative capacity of Demo 1 will amount to about 84 000 SWU/year only. By the later addition of separation stages, the separative capacities of which will be higher by the factor 3 (Demo 2), the cascade efficiency will be brought up to about 90% and the net separative capacity to 310 000 SWU/year. The data for the two extension steps have been compiled in Table 1.

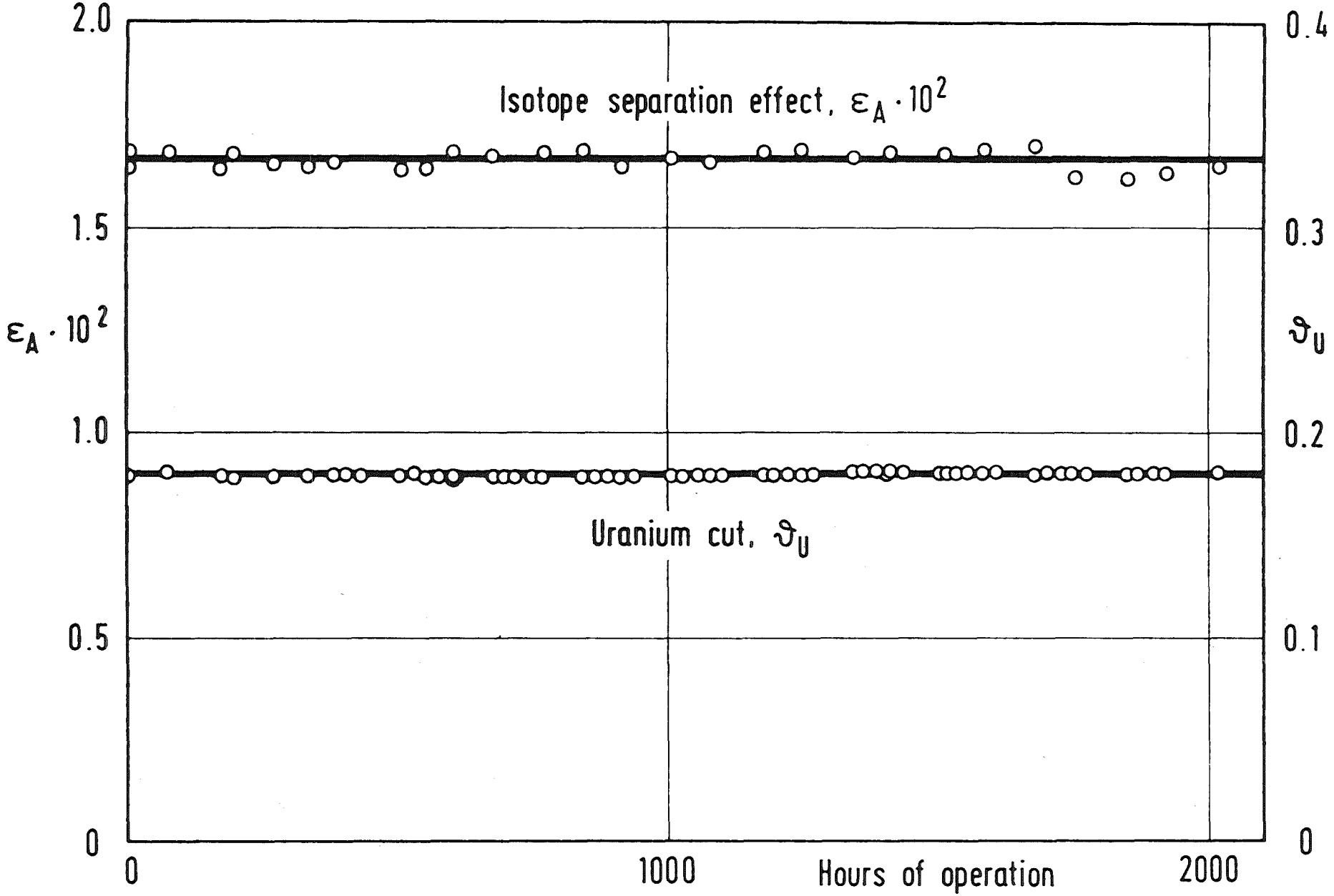


Fig.6: Testing of the separation stage type of Demo 1. The radius of the deflection groove of the separation elements is 50 µm.

	Demo 1	Demo 1 +Demo 2
Separative capacity, SWU/year	84 000	310 000
Product assay, wt % U-235	3.20	3.20
Tails assay, wt % U-235	0.51	0.34
Production rate, kg U/year with 3.2% U-235	32 000	89 000
Start of operation	1986	1988

Table 1: Data for the two sections of the demonstration plant.

4. Technology of Commercial Plants

4.1 Separation Nozzle Systems with Double Jet Deflection

For commercial separation nozzle plants the separation nozzle system with double jet deflection will be provided, as represented in Fig.7 /5/. In the double deflection system the heavy fraction of a conventional separation nozzle is split up once more in a directly connected second system so that three fractions are produced in total. The intermediate fraction is recycled within the separation stage to the suction side of the compressor. This improves the separation effect as well as the cut of the stage so that a smaller number of stages is required for a given separation task. Although the effective UF_6 throughput of the stage is decreased by recycling the intermediate fraction, the separative capacity of the stage becomes higher by about 10% for a given suction capacity of the compressor. Consequently, the specific energy consumption and the specific suction volume are reduced by the same proportion.

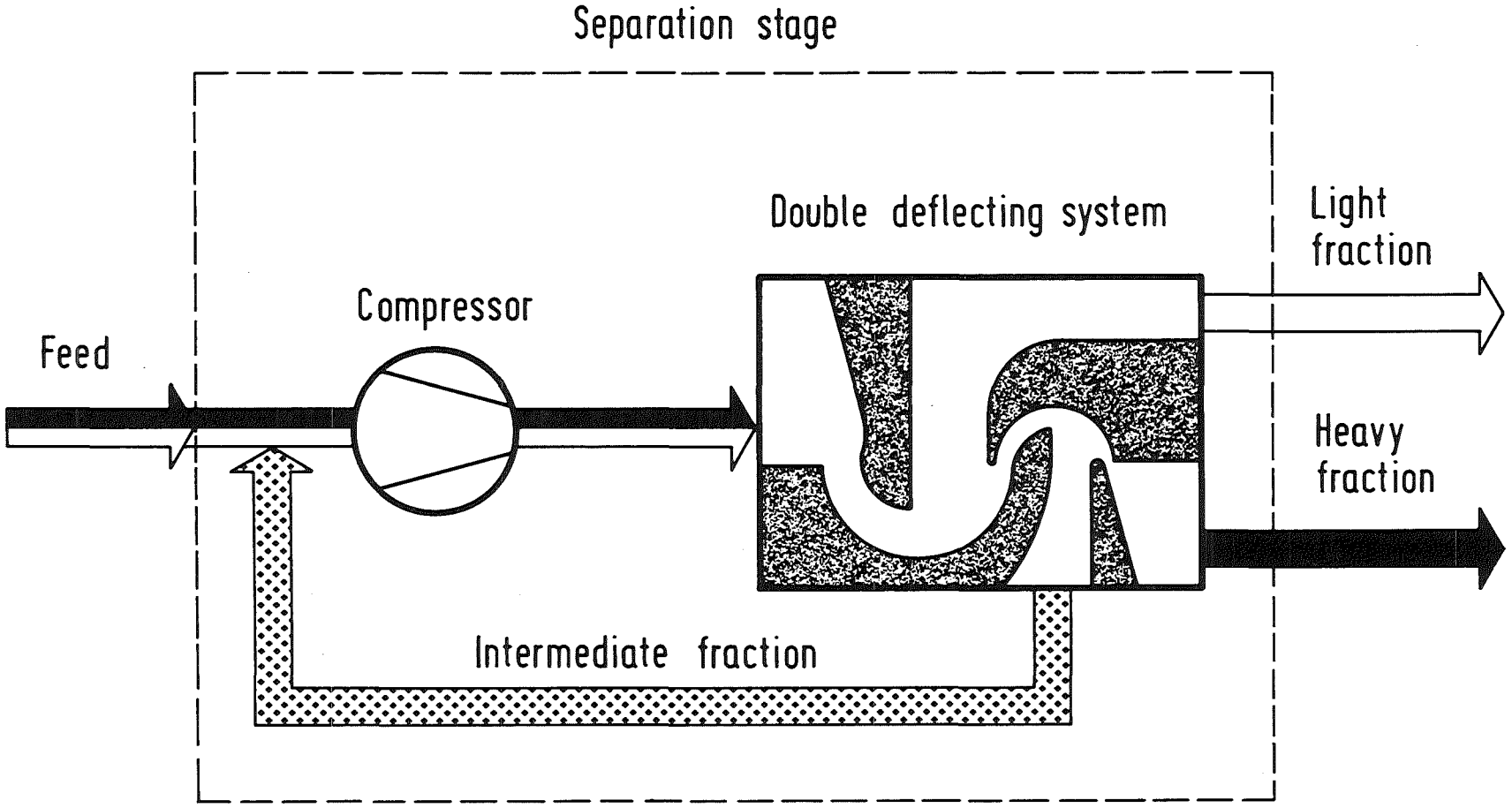


Fig.7: Principle of the separation nozzle system with double jet deflection provided for commercial separation nozzle plants.

In case the suction volume of the compressors is fixed, the reduction of the required number of stages, achieved by the double deflection system, results in a reduction of the plant capacity. Therefore, this system is of interest mainly in connection with the further increase in gas pressure planned for commercial plants (cf. Section 4.3).

Double deflection separation nozzles can be fabricated under the same methods as single deflection separation nozzles. Figure 8 shows a scanning electron microscope picture of a technical scale separation nozzle element with double deflection consisting of stacked photo-etched metal foils (Siemens AG). The mean radii of the first and second deflection grooves are 62 and 31 µm, respectively.

In Figure 9 the elementary separation effect of the uranium isotopes, ε_A, of the separation nozzle element with double jet deflection, as shown in Figure 8, has been represented as a function of the inlet pressure of the gas mixture. It can be noticed that the double deflection system which is operated at a uranium cut of 1/3 produces an elementary separation effect of the uranium isotopes, ε_A, of more than 2%.

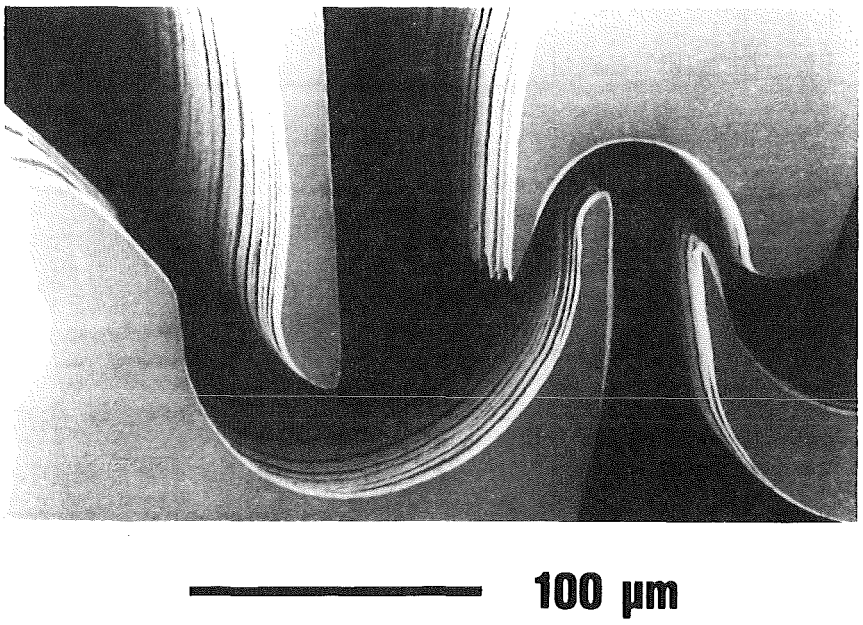


Fig.8: Detail picture of a technical scale separation nozzle element with double jet deflection, produced by stacking photoetched metal foils. The mean radii of the deflection grooves are 62 and 31 µm.

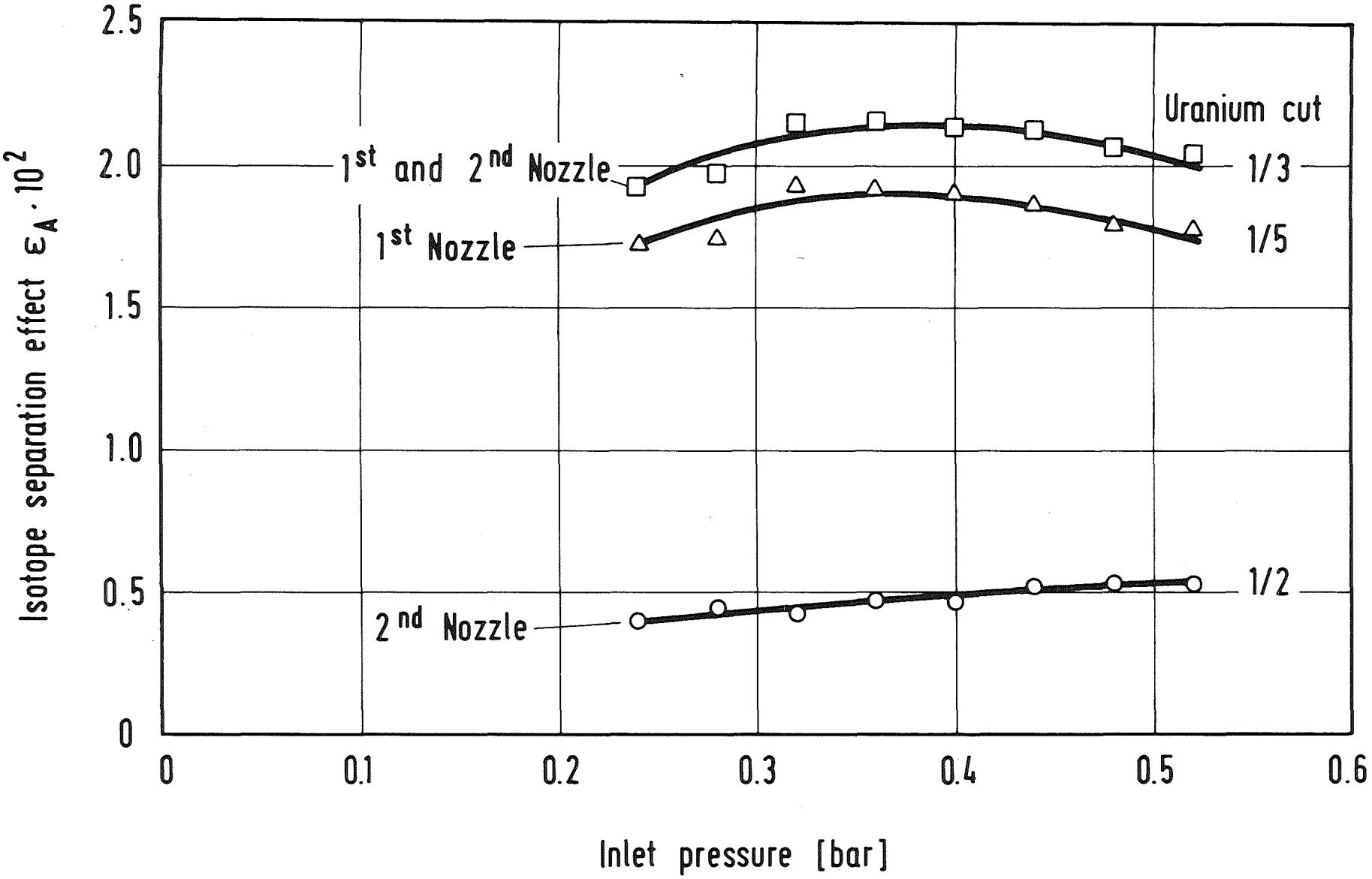


Fig.9: Elementary separation effect of the uranium isotopes, ε_A, of the technical scale separation nozzle element shown in Fig.8 with double jet deflection, as a function of the inlet pressure. Operating conditions: Composition of feed gas 3 mol% UF_6, 97 mol% H_2, expansion ratio = 2.1.

4.2 Separation of UF_6 and Light Auxiliary Gas by Double Deflection Stages

In the First Cascade, the separation of UF_6 and light auxiliary gas at the top of the cascade is performed by means of a single deflection pre-separation stage in combination with a system of cryoseparators (cf. Chapter 2). These cryoseparators as well as the additional cryogene-rating units will remain unchanged, when the First Cascade will be extended into Demo 1. This is technically feasible by use of a double deflection pre-separation stage which separates UF_6 and light auxiliary gas much more effectively than a single deflection pre-separation stage. In this way, the UF_6 stream into the cryoseparators can even be decreased considerably, although the operating pressure of Demo 1 and, hence, the UF_6 transport into the pre-separation stage are increased by a factor 2.

In case of commercial plants, the further increase in the operating pressure by a factor 3 would result in an extremely high portion of expenditure for cryoseparation in the overall investment and operating costs for isotope separation. Therefore, cryoseparation will be substituted completely by additional gas separation stages equipped with double deflection systems.

The advantage of double deflection in gas separation is evident from Fig.10 which shows the measured enrichment factor, α, of the light auxiliary gas as a function of the internal reflux rate Z of the double deflection stage. The H_2 cut has been fixed to the value of θ_Z=0.974 according to the given operating conditions of the isotope separation cascade. In case of single deflection (Z=0), the gas enrichment factor is α=2.35, while double deflection with an internal reflux rate of Z=0.5 gives a gas enrichment factor of α=23.

A schematic representation of a double deflection cascade for separation of UF_6 and H_2 is shown in Fig.11. It is obvious that the requirements of gas separation with less than 1 ppm UF_6 in H_2 are met by using three double deflection stages connected in series.

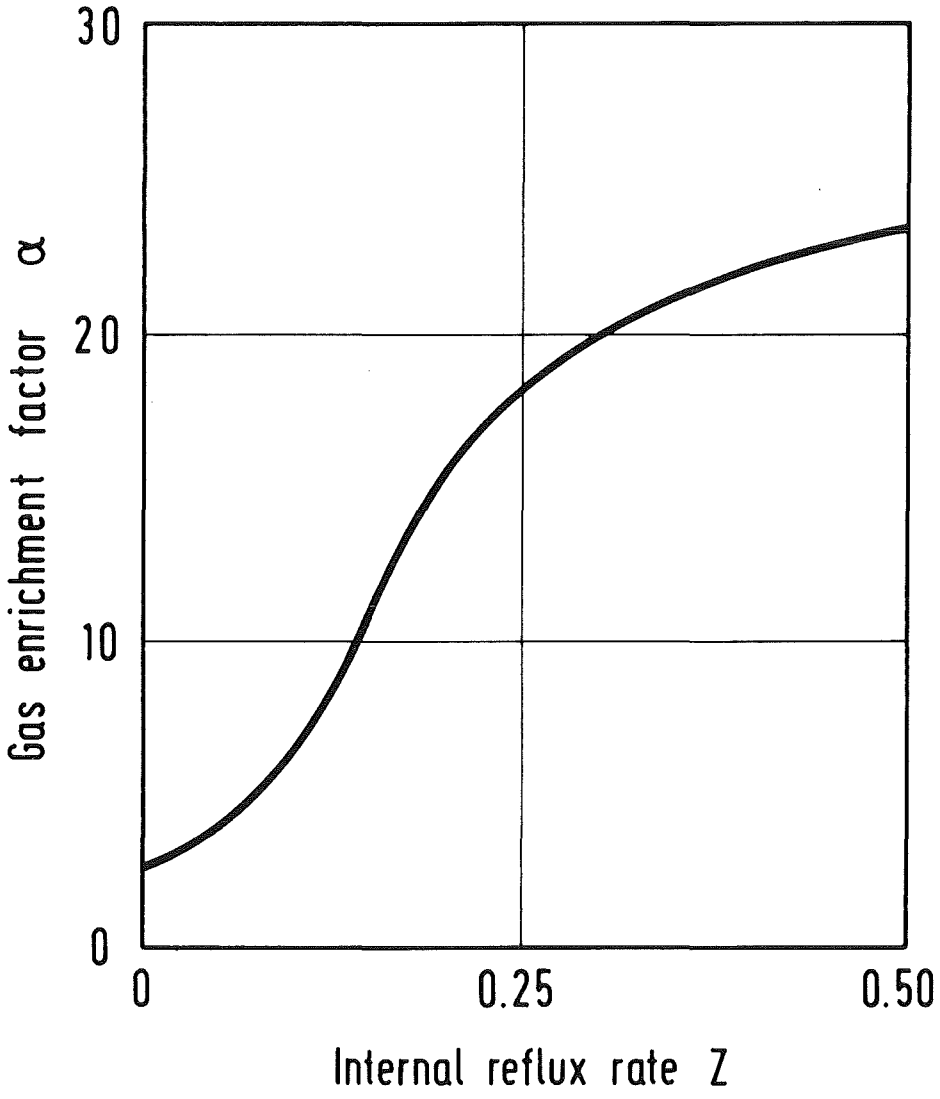


Fig.10: Enrichment factor of H_2 versus internal reflux rate Z for a pre-separation stage equipped with double deflection systems; Z is the ratio of the gas stream in the intermediate fraction to the gas stream fed into the stage (cf. Fig.7).
Operating conditions: composition of feed gas 0.8 mol% UF_6, 99.2 mol% H_2, H_2 cut θ_Z=0.974, expansion ratio=3.0.

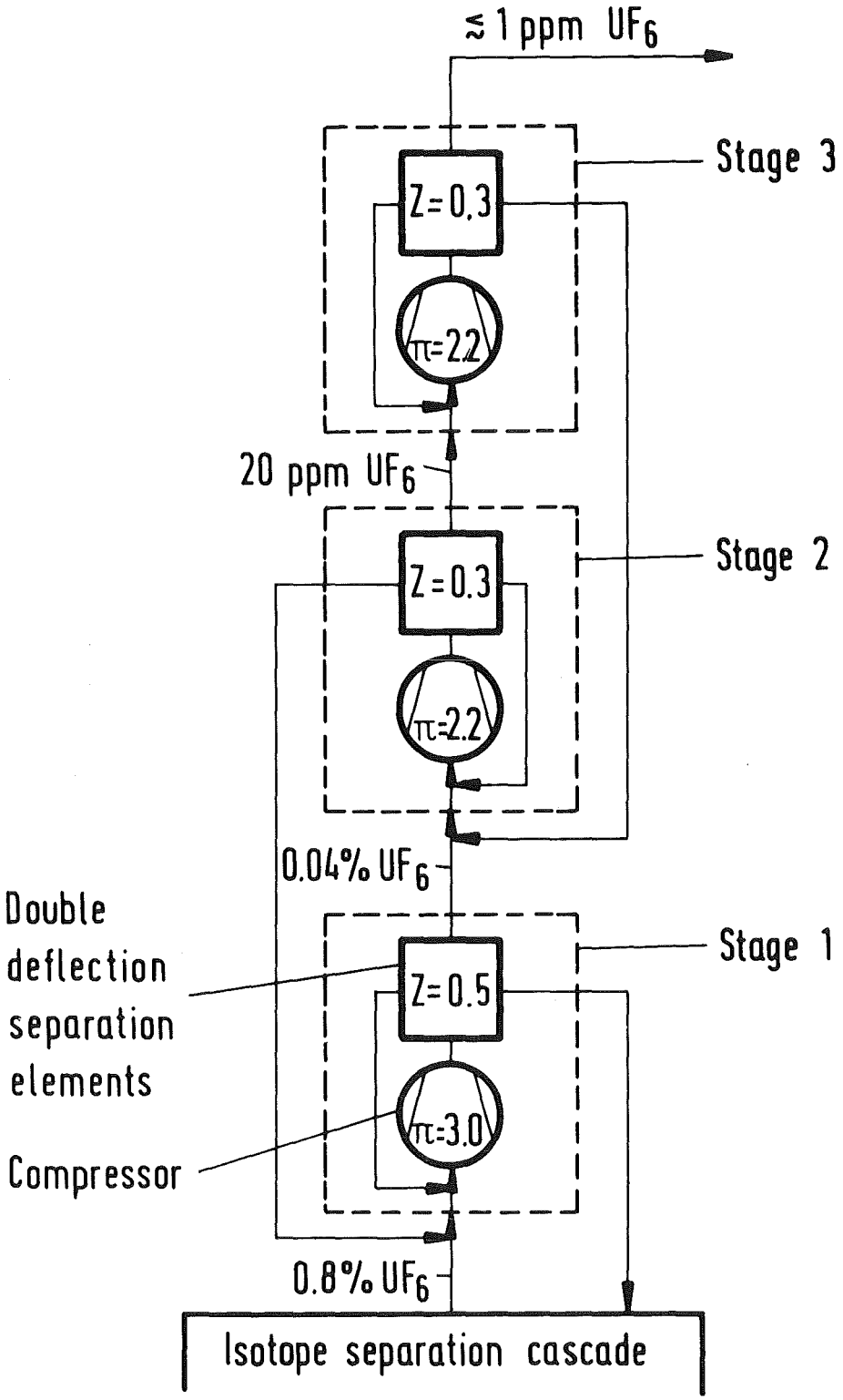


Fig.11: Conceptual design of a cascade of double deflection stages for separating H_2 and UF_6 (π=compression ratio, Z=internal reflux rate, cf. Fig.10).

4.3 Separation Nozzle Systems with Extremely Small Characteristic Dimensions

The most economical way of increasing the production capacity of the separation nozzle process lies in raising the optimum operating pressure. In this case, the expenditure for the compressors, pipework, valves and control devices remains almost unchanged; however, the separative capacity of the enrichment plant increases proportional to the operating pressure. Since the UF_6 is highly diluted by the light auxiliary gas, a further increase in the operating pressure by a factor 3 over that of Demo 1 (cf. Chapter 3) is possible without the risk of UF_6 condensation.

The reduction in the characteristic dimensions of the systems, which is required for raising the optimum operating pressure, poses substantial difficulties to the separation element fabrication techniques to be applied in the First Cascade and in the demonstration plant. Therefore, the Karlsruhe Nuclear Research Center has taken up development work for a technique based on combined lithography and microgalvanic deposition (LIGA) which allows to fabricate three times smaller separation nozzle structures with the required accuracy. By irradiation and development of a resist layer a negative of the separation nozzle structures is first prepared which, subsequently, is filled with metal by electrodeposition. The work is performed jointly with Siemens AG, Munich, and the Fraunhofer Gesellschaft (IFT), Munich.

As in the photo-etching technique, a multitude of separation nozzle structures are produced in parallel by the LIGA method. Figure 12 shows a detail picture, taken by a scanning electron microscope, of a 40 µm thick nickel foil with double deflection nozzles produced by the LIGA method. The mean radii of the deflection grooves are 20 and 10 µm. To produce the lithographic molds of the separation nozzles, synchrotron radiation generated by the DORIS electron storage ring of Deutsches Elektronensynchrotron (DESY), Hamburg, was used. The x-ray masks of the separation nozzles were made at the electron synchrotron 2 of Bonn University.

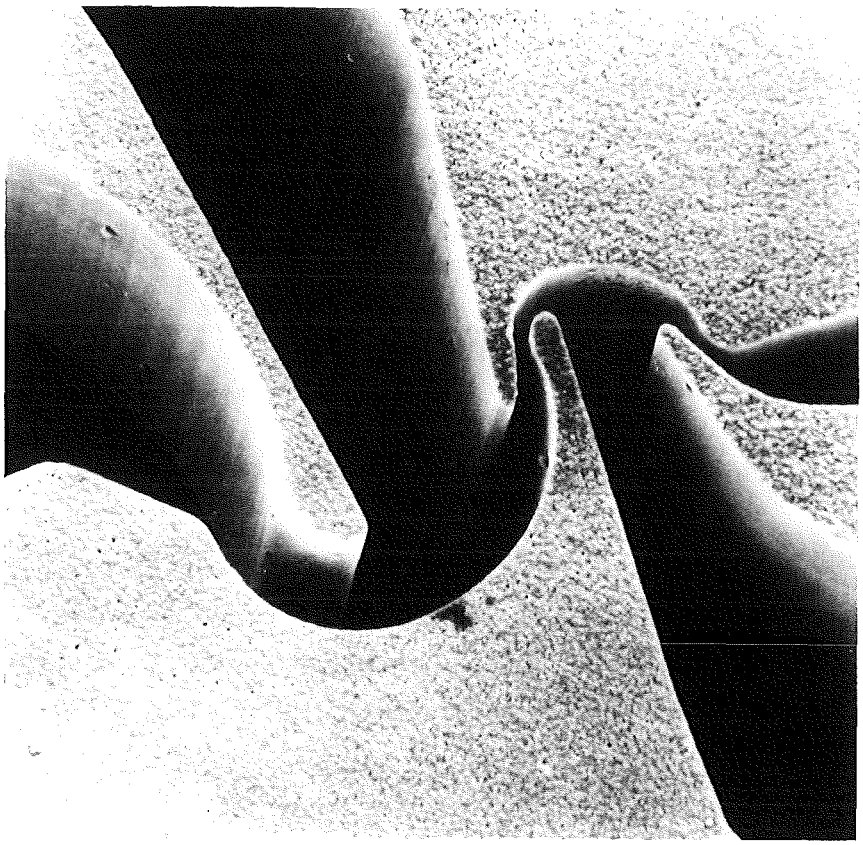


Fig.12: Detail picture of a 40 µm thick nickel foil produced by the LIGA technique with structures of double deflection separation nozzles. The mean radii of the deflection grooves are 20 and 10 µm.

It is expected that separation nozzle structures with a much higher ratio of slit length to slit width than that of the nozzle shown in Fig.12 can be produced by using an improved version of the LIGA method. This would allow to avoid stacking of single foils and would result in considerable savings of the manufacturing process.

Moreover, the possibility is indicated of using the metal structure formed by combined lithography and microgalvanic deposition as a tool for producing separation nozzle negatives by simple molding of plastics.

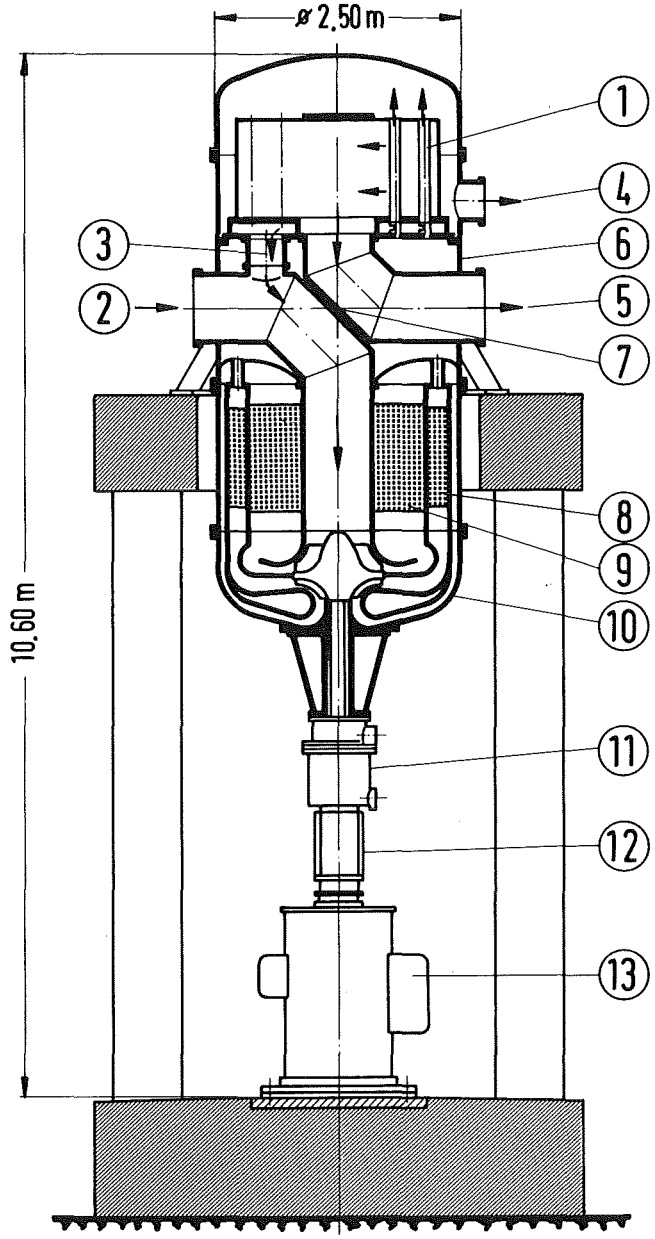
In this way, mass production of the separation nozzle structures can be made to become independent of the relatively costly irradiation sources.

With the results available now we can count on technical-scale application of the LIGA technique as from 1985. Therefore, the plans for erecting commercial separation nozzle plants are based on a pressure higher by the factor 3 against that applied in Demo 1.

4.4 Larger Scale Separation Stages

For commercial separation nozzle plants separation stages with compressor suction capacities of 100 000 and 300 000 m^3/h are being developed at the Karlsruhe Nuclear Research Center in cooperation with the German-Brazilian company NUSTEP (SR 100 and SR 300).

Figure 13 shows a cross section of the separation stage SR 100 intended for operation with double deflection separation nozzles. The mixture inflowing at 2 is compressed by a two-stage radial compressor with intermediate and final cooling and enters the tubular separation elements 1 from below. They are equipped with the double deflection separation nozzles and several gas distribution channels running parallel to the tube axis. The heavy fractions escaping at the top end of the separation nozzle tubes leave the stage via the pipe connection 4. The intermediate fractions are collected in a flat space underneath the separation elements and fed into the suction pipe of the stage through the pipe connection 3. The light fractions leaving the separation nozzle tubes in the horizontal direction over their total lengths depart from the stage via the pipe connection 5. Figure 14 shows the stage shortly before its completion. Its diameter is 2.5 m.



1 = Separation nozzle tubes
2 = Feed gas
3 = Intermediate fraction
4 = Heavy fraction
5 = Light fraction
6 = Housing of separation nozzle tubes
7 = Intermediate section
8 = Final cooler
9 = Intercooler
10 = Compressor
11 = Gear
12 = Coupling
13 = Motor

Fig.13: Cross section of the separation stage SR 100 scheduled for operation with double deflection separation nozzles.

The three times larger stage SR 300 with a compressor suction capacity of 300 000 m^3/h and a diameter of 4.0 m resembles SR 100 in its layout (Fig.15). It is likewise scheduled to start operation in 1982.

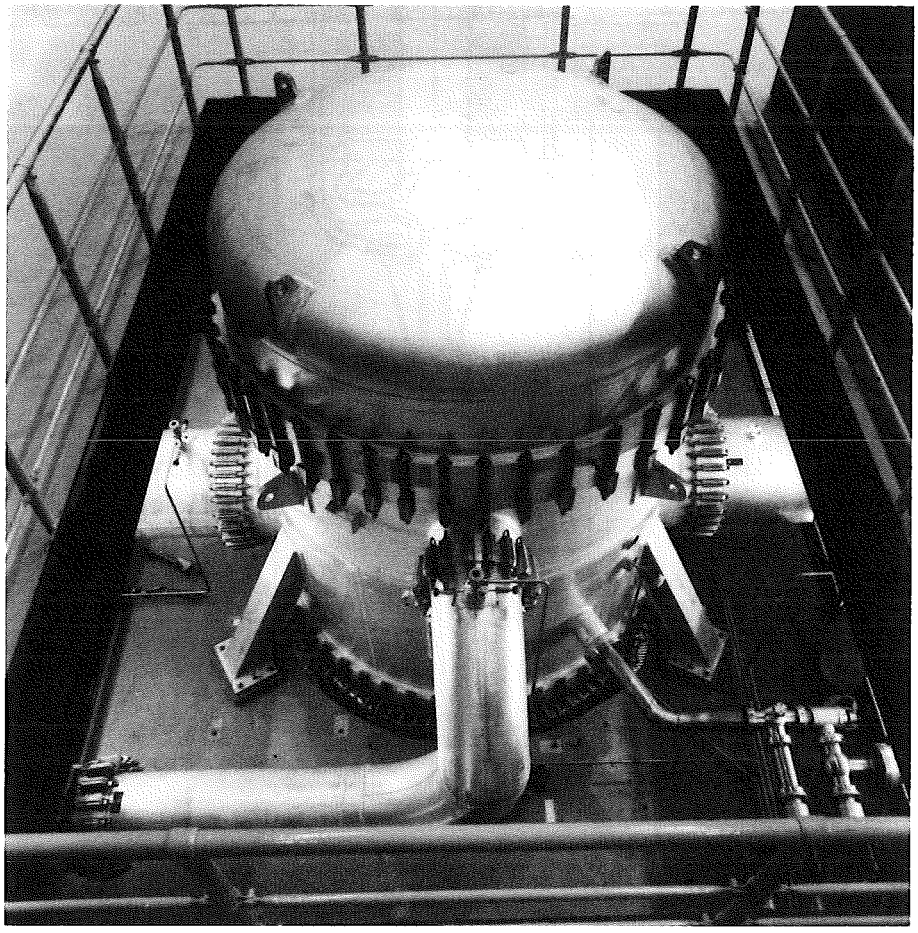


Fig.14: Prototype of the separation nozzle stage SR 100 with a compressor suction capacity of 100 000 m^3/h. Diameter 2.5 m.

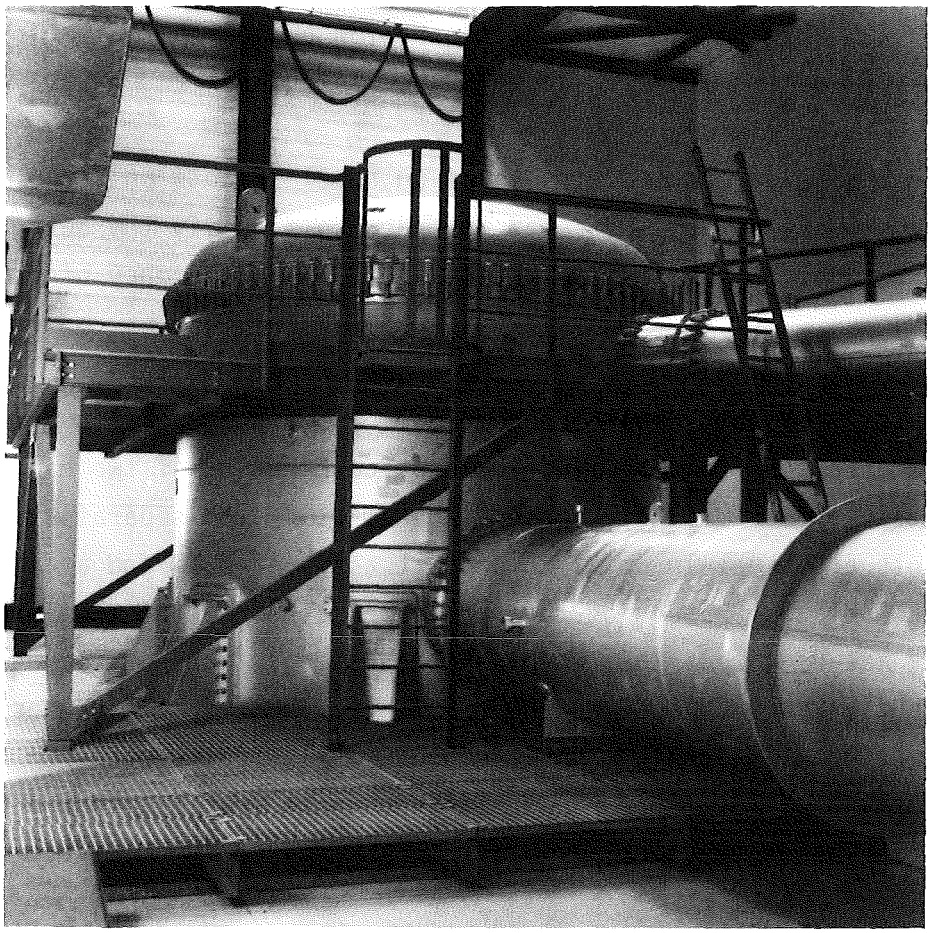


Fig.15: Prototype of the separation nozzle stage SR 300 with a compressor suction capacity of 300 000 m^3/h. Diameter 4.0 m.

5. Design and Economic Aspects of Commercial Plants

Figure 16 shows the three types of separation nozzle stages presently available. When using LIGA type separation elements, the separative capacities of the stages will be 2 400, 7 200 and 22 000 SWU/year.

In the design of commercial separation nozzle plants only two types of stages will normally be used in order to simplify the design of the cascades. This allows to obtain a cascade efficiency of about 90%.

In Table 2 the data have been compiled of two commercial separation nozzle plants which can be realized by combination of two each of the stage types available, provided that LIGA type separation elements are used. To obtain a product assay of 3.2% and a tails assay of 0.25% U-235, 96 each of the smaller and 160 each of the larger stages are required. The two plants have separation work capacities of about 1 200 000 and 3 700 000 SWU/year. Their specific energy consumption of slightly more than 3000 kWh/SWU corresponds to a consumption of roughly 4.5% of electricity generated with the product in light water reactors.

	Small Plant	Large Plant
Product assay, % U-235	3.2	3.2
Tails assay, % U-235	0.25	0.25
Number of small stages (SR 33)	96	-
Number of medium-sized stages (SR100)	160	96
Number of large stages (SR 300)	-	160
Production capacity, SWU/year	1 257 000	3 776 000
Total power supply, MW	443	1 322
Specific energy consumption, kWh/SWU	3 084	3 063
Feed requirements, million kg uranium/year	1.9	5.7
Uranium inventory, kg	2 400	7 500

Table 2: Data of two commercial separation nozzle plants which can be realized by combination of two each of the separation nozzle stages available, if LIGA type separation elements are used.

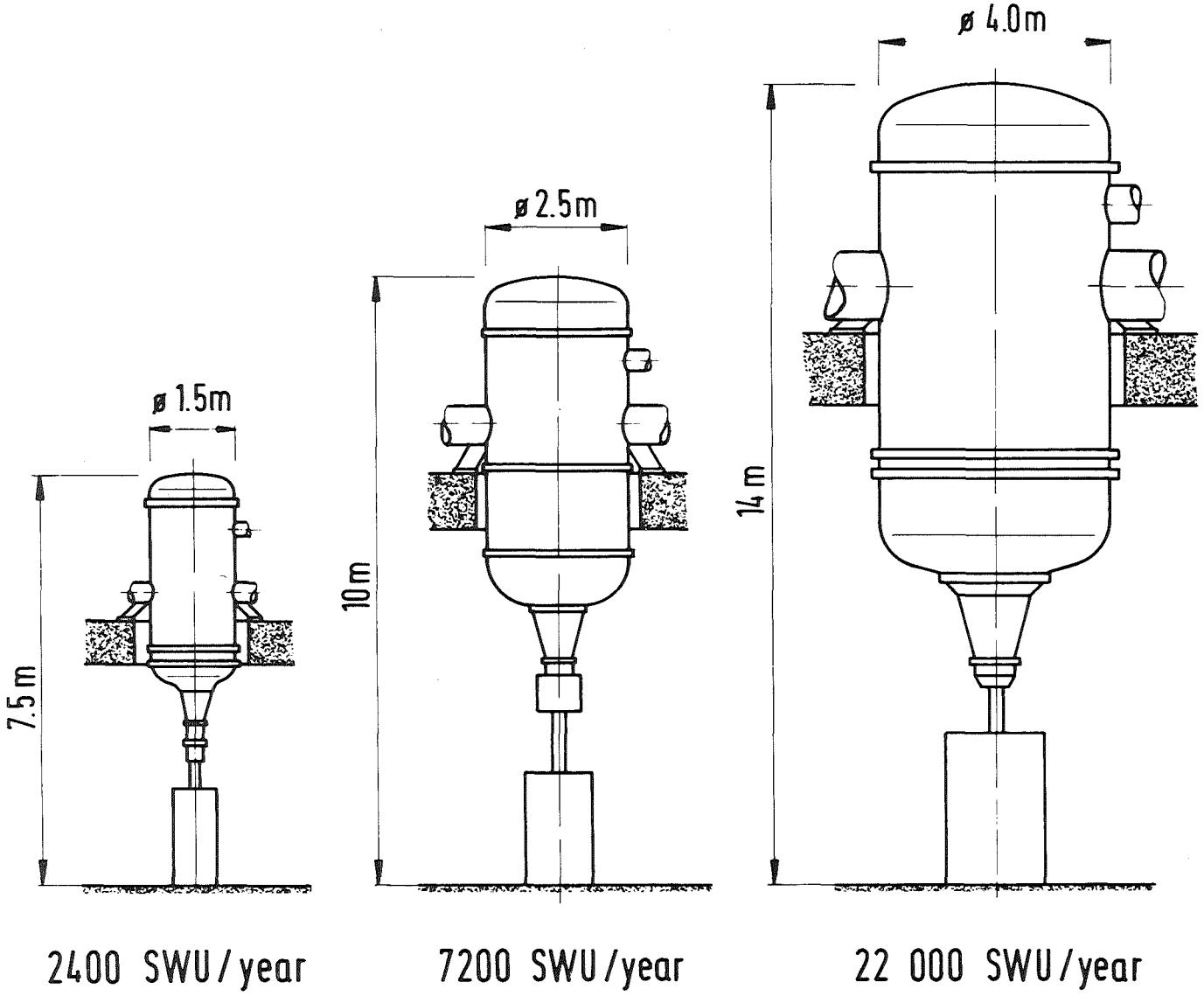


Fig.16: The types of separation nozzle stages presently available for commercial enrichment plants. The separative capacities of the stages refer to LIGA-type separation elements.

Table 3 shows a breakdown of the separative work costs for both plants. The costs of investment were extrapolated to late 1981 on the basis of earlier quotations for components. With the usual extras for engineering, contingencies, costs incurred by the plant operator and interest during construction a total of investment costs for both plants of approximately US-$ 700 and 1300 million, respectively, are calculated.

	Small Plant	Large Plant
Investment costs for the plant inclusive of buildings, million US-$	431	865
Contingency and engineering costs, million US-$	128	193
Costs incurred by plant operator during the period of construction, million US-$	50	70
Interest during construction, million US-$	92	169
Total investment costs, million US-$	701	1 297
Production capacity, SWU/year	1 257 000	3 776 000
Specific total investment costs, US-$/SWU/year	560	350
Specific fixed costs = 20% of the specific total investment costs with 95% plant availability, US-$/SWU	118	74
Specific power costs based on US-$ 0.015 per kWh, US-$/SWU	46	46
Separative work costs, US-$/SWU	164	120

Table 3: Determination of the separative work costs of the two commercial separation nozzle plants (cf. Table 2).

This corresponds to specific total investment costs of US-$ 560 and US-$ 350 per SWU/year, respectively. The calculation of the product costs was based on the assumption that the annuity and the annual expenses for handling, maintenance and repair amount to 20% of the

total investment costs. Power costs of US mills 15 per kWh were assumed because it can be rightly supposed that the plant will be built at a place where power costs are relatively low.

This results in costs per unit of separative work of US-$ 164 for the small plant and of US-$ 120 for the large plant.

It is evident from the estimate that at least the large plant will be capable of yielding profits. It is remarkable that an economical production of reactor fuel can be achieved already with a capital investment of about one billion US-$.

6. Licensing of Separation Nozzle Plants.

Besides hydrogen, helium can be used as the light auxiliary gas in the separation nozzle process*). It offers essential advantages due to its absolute chemical neutrality; however, the specific energy consumption increases by about 25%. The specific investment costs calculated for helium and hydrogen are approximately equal. With the cost structure shown in Table 3 this implies an increase in the product costs of 7.5 and 10%, respectively. On the other hand, if helium is used, quite a number of safety requirements can be dispensed with, which simplifies licensing considerably. Therefore, the question whether hydrogen or helium is better suited must be examined in each individual case, with the power costs playing a major role in decision making.

*) The cost of helium does not play a part in considerations relating to economy, since the amount is relatively small and the gas is recirculated.

The licensing procedure is facilitated by the fact that the separating cascades of the commercial plants are still working slightly below atmospheric pressure. Overpressure occurs only in the interconnections of the compressor and the separation elements which parts will be surrounded by low-pressure zones, when LIGA elements are used. Therefore, there is no danger of UF_6 release. In addition, it should be noted that the uranium inventory of separation nozzle plants is of the order of some metric tons only (cf. Table 2).

7. Safeguards

Application of the separation nozzle method in Brazil is subject to safeguards by the International Atomic Energy Agency. The task of this organization is facilitated by the fact that no restrictions due to classification have been imposed on the development and application of the separation nozzle method as it cannot be misused in a clandestine facility.

For safeguarding commercial separation nozzle plants it is advantageous that they will contain no buffer with enriched uranium (cf. Section 4.2). The short equilibrium time of the plants permits accurate surveillance and control of the production rate which will be advantageous for safeguards as well as for economy and plant operation.

8. Conclusions

An increase in the elementary separation effect for given operating conditions constitutes one of the most attractive goals of development work, since all specific expenditures and, hence, the separative work costs are inversely proportional to the square of this quantity.

The single deflection system the principle of which is represented in Fig.1 is the result of extensive optimization work. But on account of the multitude of parameters to be varied, optimization cannot at all be considered as finalized. This applies even more to the double deflection system shown in Fig.7, which involves much more parameters.

For the separation nozzle process no technically relevant lower limit can be stated regarding the specific energy consumption. This expenditure can be decreased to the extent as one succeeds in further reducing interfering secondary processes, above all those due to viscous effects. There is still substantial development potential in this field /6/.

The investment costs given in Table 3 were calculated on the basis of conservative quotations. In particular, no major efforts have been made to reduce the costs by development of special fabrication techniques for the components of separation nozzle plants. For example, all cost assessments were based on the assumption that aluminium alloys which are being used in the Demo plant will also be used in the commercial plants. Up to now, no efforts have been taken to reduce costs by using nickel plated steel which is standard in gaseous diffusion plants as a substitute for aluminium alloys. In addition, the costs for separation elements which come to one quarter of the total investment costs, include considerable extra charges for contingencies.

In summary it can be stated that the separation nozzle process has a good chance to contribute significantly to the production of enriched uranium in the future.

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