Developments in the Uranium Enrichment Industry

by Ole Pedersen

Until a few years ago, the uranium enrichment market was characterized by one major supplier, one technology, on set of terms and conditions for supply, and ample capacity to meet demand. Now the market is passing through a period of extraordinary change and uncertainty. It is likely that some time will elapse before more stable conditions are restored.

The present changes have been brought about by the introduction of new technologies and new suppliers, which has resulted in a growing competition for shares of the market and a diversification of terms and conditions for supply. The major uncertainties are the size of the future market for enriched uranium and the closely related problem of whether too little, too much or adequate enrichment capacity to meet future demand will be available when needed. Lying further in the future is the possible development of new technologies for uranium enrichment.

The world's major supplier, the United States Energy Research and Development Administration (ERDA), since mid-1974 has fully booked, under long-term contracts, its present and future committed capacity, and has since then been unable to accept new contracts. Also, the question of government or private ownership of enrichment facilities in the USA has become controversial with the result that proposals for expansion of enrichment capacity, made in 1974, have not yet been decided on.

ENRICHMENT TECHNOLOGIES

Uranium enrichment is a necessary component of the fuel cycle of light water reactors (LWR), advanced gas-cooled reactors (AGR), and high temperature reactors (HTR). These reactors particularly LWR's, dominate the market. In 1976, the capacity of enriched uranium reactors was 87% of all operating reactors, and the latest estimates are that the percentage will be 93% in 1990, and about 90% in the year 2000. These reactors will need enrichment services far into the next century. The market for the supply of enrichment services is already of the order of hundreds of million of US $ per year and will in 1980's be a multi-billion dollar market.

Uranium, as it occurs in nature, contains 0.711 weight percent of the light and fissile isotope uranium-235. The operation of light water reactors requires uranium with a content of U-235 of around 3%. The purpose of the enrichment process is to separate the natural

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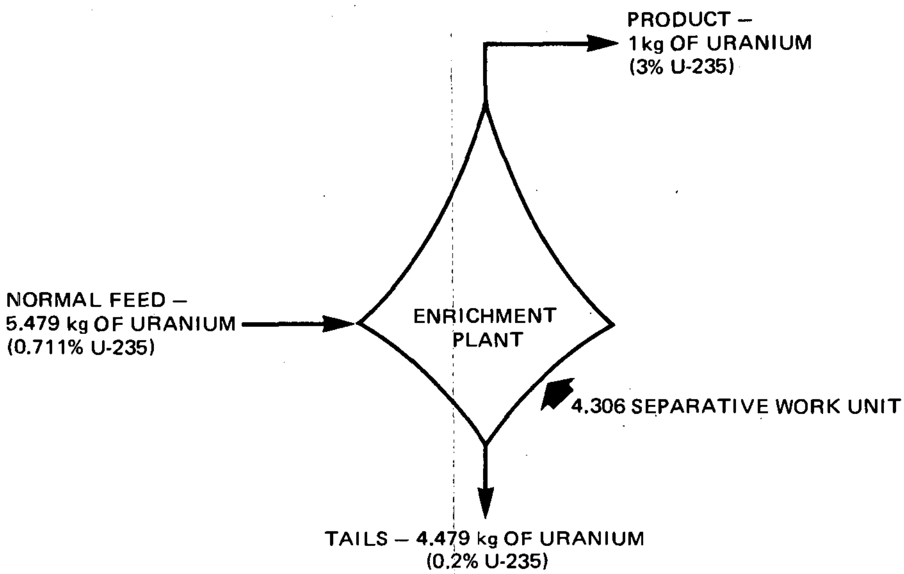
uranium into enriched uranium containing U-235 at a percentage higher than the natural content (the enrichment percentage) and depleted uranium containing U-235 at a percentage lower than the natural (known as "tails assay"). The effort necessary for the separation of the isotopes is measured in separative work units, known as SWU's.

If, for instance, one kilogram of 3% enriched uranium is needed, and the tails assay is to be 0.2%, then an input of 5.479 kg of natural uranium and 4.306 SWU's are required. This leaves 4.479 kg uranium (tails) depleted to 0.2% uranium-235 (see Figure 1).

Figure 1:
Example of Separative Work Required for Uranium Enrichment



The enrichment methods currently in industrial use or under pilot plant testing all require uranium hexafluoride (UF_6) as the feed material. The reason is that this uranium compound becomes gaseous at temperatures above 57°C. The uranium ore from the mine must therefore first be purified and converted into uranium hexafluoride before it can be used as feed for the enrichment plants.

Gaseous diffusion:

Although several methods for isotope separation were known before nuclear fission was discovered, the main technology presently in use for uranium enrichment on an industrial scale is the gaseous diffusion process. This technology is used in the USA, which until a few years ago was practically the only supplier of enrichment services to countries with market economies. It is also the technology used in the USSR, practically the only supplier of enrichment services to countries with centrally planned economies. In addition, gaseous diffusion is the technology used in the smaller enrichment plants originally built in France and the United Kingdom.

The fact that gases with different molecular weights can be separated by diffusion through a porous medium was discovered in 1846. If the pores have a suitable size, the lighter gas molecules pass through the porous medium, generally known as the membrane or barrier, at rates higher than the heavier molecules. The first industrial-scale use of the process was in 1945 in the USA at the plant at Oak Ridge, Tennessee.

The diffusion of a part of the gas through the barrier is obtained by means of a compressor associated with a heat exchanger for removing the heat of compression. The difference of weight between the molecules of UF_6 containing the lighter isotope uranium-235 and those containing the heavier uranium-238 is very small. Consequently, the degree of enrichment accomplished by one pass through a barrier is also very small and the operation has to be repeated many times. Thus, the gas has to go through a large number of stages, each consisting of compressor, barrier and heat exchanger. The sequence of stages constitute what is called the cascade.

The separation per stage is so small that in order to produce uranium enriched to 3% uranium-235 from natural uranium, with a tails assay of 0.25% uranium-235, the cascade will consist of about 1200 stages arranged in series. However, each stage can be built with a capacity large enough to obviate the need for parallel cascades.

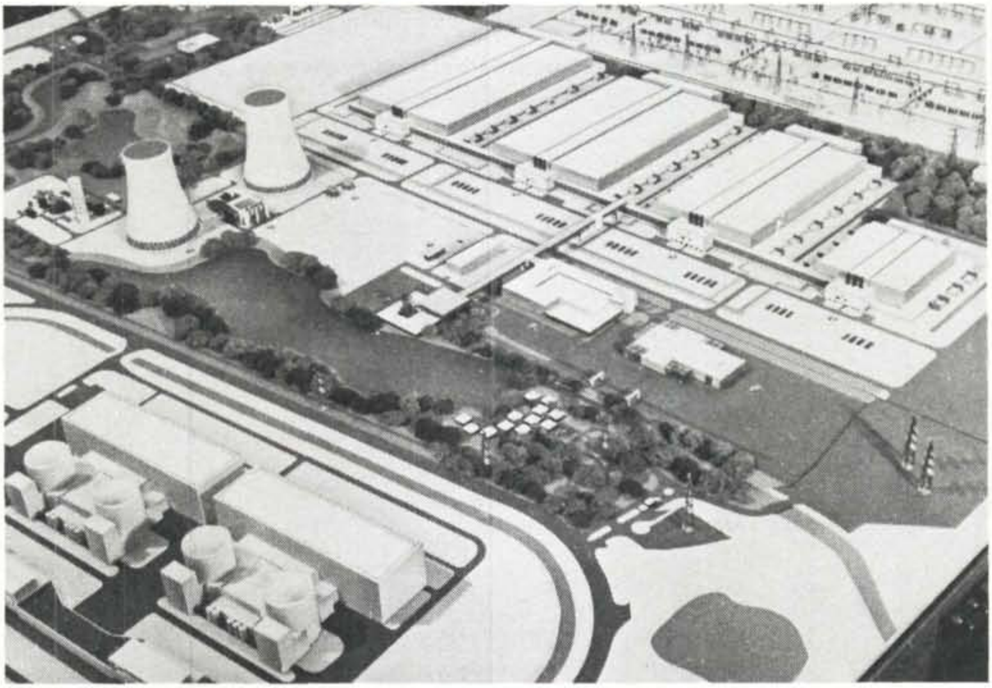
Centrifuge separation:

Experiments on the use of centrifuges for the separation of mixtures of gases of different molecular weight were carried out at the end of the 19th century. An experimental centrifuge plant for separation of uranium isotopes in UF_6 was operated in the 1940's. However, it was abandoned in favour of gaseous diffusion mainly because of problems with materials and bearings which were unable to withstand the very high rotational speed and centrifugal forces required.

The development of stronger and lighter materials, of new bearings, and of improved designs of centrifuges has brought the centrifuge isotope separation back into use in Europe and the USA. Experimental work is also being done in Australia and Japan. The attraction of the centrifuge method is that, at its present stage of development, it permits separation per stage about two orders of magnitude larger than with other methods in use, and that the energy consumption is only about 10% of that of the gaseous diffusion process. A disadvantage is that much smaller quantities can be processed in each centrifuge than in a gaseous diffusion stage. Consequently very many centrifuges must be operated in parallel and the total number of centrifuges therefore must be much larger than the number of separation stages in the gaseous diffusion process in order to produce the same output.

Nozzle separation:

In this process, a jet of gaseous uranium heaxafluoride mixed with helium or hydrogen is expanded through a slit and deflected by a curved wall. As a result of centrifugal and other forces, this leads to a partial separation of the components. The gas moving close to the



Model of EURODIF's Tricastin plant in France. The plant will use gaseous diffusion to enrich uranium.

Aerial view of the Tricastin plant site. Start-up is scheduled for December 1978.

Table 1: Status of Uranium Enrichment Plants and Projects (As of January 1977)

Owner	Process	Location	Capacity (Million SWU's Per Year)	
OPERATING PLANTS				
USA (ERDA)	GDP	Oak Ridge, Tenn.	4.73	
	GDP	Paducah, Ky.	7.31	
	GDP	Portsmouth, Ohio	5.19	
			17.23 (Total)	
USSR	–	[a]	[a]	
France (CEA)	GDP	Pierrelatte	~ 0.5	
United Kingdom (UKAEA)	GDP	Capenhurst	~ 0.5	
Chinese People's Republic	–	[a]	[a]	
URENCO	CP	Capenhurst, England Almelo, Holland	0.065	
Karlsruhe Nuclear Centre/Steag A.G.	NP	Karlsruhe, FRG	Pilot Unit	
PLANTS UNDER CONSTRUCTION				**Scheduled Operation**
Improvement and Uprating of ERDA Plants	GDP		10.5[b]	1975–1981
EURODIF (France, Belgium, Iran, Italy, Spain)	GDP	Tricastin, France	10.8	1978–1981
COREDIF (EURODIF, France, Iran)	GDP	[c]	10	Late 1980's[c]
URENCO	CP	Capenhurst, England Almelo, Holland	0.4 to 2.0	1977–1982
South Africa	NP	Valindaba, SA	Pilot Unit	?

deflecting wall is enriched in the heavy isotope uranium-238, while the light isotope uranium-235 accumulates in the remaining gas. The helium or hydrogen added to the gaseous UF_6 facilitates the process in various respects and enhances the separation. This process was considered in the early 1940's but not used. It is now being developed in the Federal Republic of Germany.

In 1970, it was announced that a new process for uranium isotope separation had been developed in South Africa and in 1975 some details of the process were given. It appears to be related to the jet nozzle process. It is known under the name "stationary-wall

Owner	Process	Location	Capacity (Million SWU's Per Year)	Scheduled Operation
PLANTS UNDER ACTIVE CONSIDERATION				
USA (ERDA)	GDP	Portsmouth, Ohio	8.75[b]	1984
Uranium Enrichment Associates[d]	GDP	Dothan, Alabama, USA	9[d]	
Exxon Nuclear Co.	CP	USA	1.0 to 3.0	1982–1986
Centar Associates	CP	USA	0.3 to 3.0	1982–1988
Garrett Nuclear Corp.	CP	USA	0.3 to 3.0	1982–1989
URENCO	CP	Capenhurst, England Almelo, Holland Possibly FRG	[e]	[e]
Brazil	NP	Brazil	0.18	?
Japan (PNC)	CP	Japan	Pilot Unit	1979
LASER ISOTOPE SEPARATION EXPERIMENTS[f]				**Working Material**
Avco — Exxon		Everett, Mass, USA		U Metal vapour
Lawrence Rad. Lab.		Livermore, Calif.,		U Metal vapour
Los Alamos Sci. Lab.		Los Alamos, USA		UF_6 vapour

Note: Processes are indicated as follows:

GDP: Gaseous diffusion process
CP: Centrifuge process
NP: Nozzle process

[a] Capacity and location not published.
[b] This additional capacity is not planned to serve new customers but to reduce tails assay for all ERDA plants; see explanation in text.
[c] Construction decided but not yet started and location not yet announced; operational time-table flexible to meet demand; see text.
[d] No longer under active consideration; see text.
[e] Capacity to be expanded as additional contracts are signed.
[f] Such experiments are also carried out elsewhere.

centrifuge". A pilot plant has been constructed at Valindaba near Pretoria and a prototype module for an industrial-size plant is being constructed. Insufficient information is available about this process in order for it to be compared with other processes.

Laser isotope separation:

It has long been known that it might be possible to separate isotopes be selectively exciting atoms or molecules. The invention of the laser made this possibility come closer to industrial use. The theoretical possibility exists that with this process very high separation of uranium isotopes can be made in one step with low energy consumption. It would have far reaching economic and political consequences if this possibility should turn into reality. The process has succeeded on a laboratory scale but there are still many problems to be overcome before it can be developed into an economically viable, industrial-scale process.

Other processes:

There are a large number of other possible processes for isotope separation. A review of these alternatives is planned for the IAEA's Conference on Nuclear Power and its Fuel Cycle at Salzburg in May 1977.

SUPPLIERS

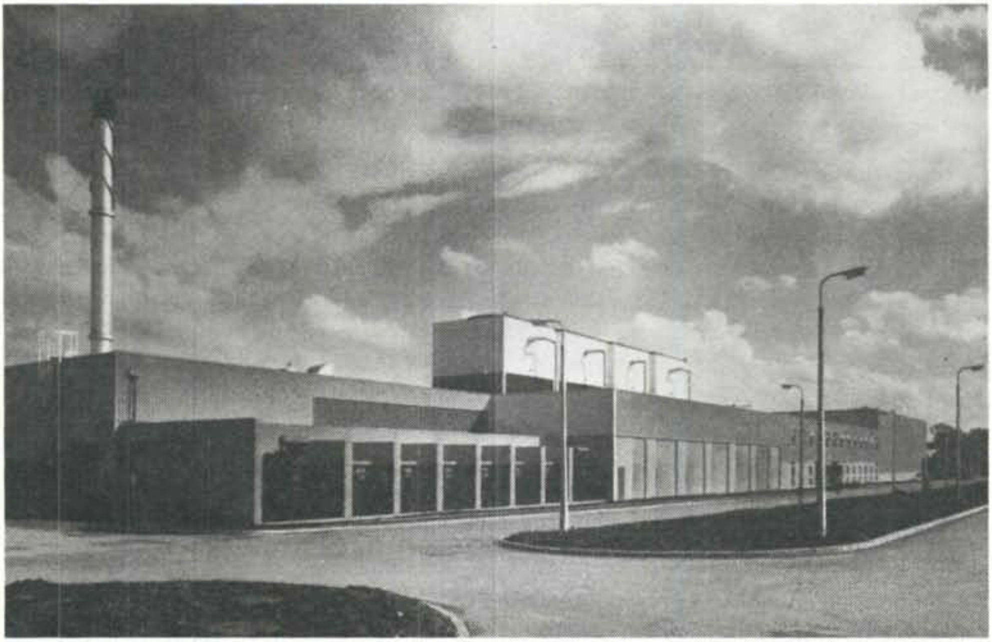
United States of America

The demand for enrichment services in countries with market economies was until mid-1974 almost exclusively met from the three large diffusion plants belonging to the United States Energy Research and Development Administration (formerly the Atomic Energy Commission). The total capacity of these plants is 17.2 million SWU per year. This capacity was for years ample to meet all demand and in addition produce a reserve of enriched uranium. It was, however, foreseen even before 1970 that the time was approaching when additional capacity would be necessary. By mid-1974, ERDA had fully booked its available capacity under long-term contracts and was from then on obliged to stop accepting new orders.

It had over many years been the policy of the USA to be an assured source of supply of enrichment services to both domestic and foreign customers. In 1974 the US President reaffirmed that the US policy would continue to be one of assurance of reliable world-wide supply. At the same time he proposed the Nuclear Fuel Assurance Act as a basis for a transition of the uranium enrichment industry from a Government monopoly to a private industry. This proposal was based on policies instituted in 1971. The proposal proved controversial with the result that until the beginning of 1977 no action was taken to expand capacities with a view to meet additional demand.

However, two actions have been taken to expand capacities but they are not intended to form the basis for further contracts to customers. The first is an improvement programme of the existing three plants. This includes the cascade improvement programme (CIP) which incorporates into the existing plants the most advanced diffusion technology. In addition, the cascade uprating programme (CUP) will permit increase of the plants' operating power levels from 6100 MW to 7400 MW (more than total electric capacity of most countries in the world). The CIP and CUP programmes are expected to be completed by 1981. They will result in an increase in capacity from 17.2 to 27.7 million SWU's per year for all three plants operated as an integrated complex. This has, however, been taken into account in the long-term contracts already concluded by ERDA and will thus not add to ERDA's contracting capacity.

Secondly, plans are in progress to add capacity of 8.75 million SWU per year to the diffusion plant at Portmouth, Ohio. Construction is scheduled to begin in spring 1977 with operation to begin in 1984, but these plans still have to be approved by the US Congress. It is not planned that this "add-on" plant, as it is known, should increase ERDA's contracting



URENCO's production plant at Capenhurst, England. The plant uses the gas centrifuge process for the enrichment of uranium.

capacity. It is needed to reduce the tails assay (in other words, to increase the percentage of U-235 that is extracted) for the integrated diffusion plant complex. In the absence of plutonium and uranium recycle, fulfilment of ERDA's enrichment services contracts would require operation of the improved and up-rated plants without the "add-on" plant at a tails assay as high as about 0.37% U-235. This would require a much higher quantity of feed of natural uranium than is at present used with operating tails assay of 0.25%. The "add-on" plant would thus considerably reduce the requirement for natural uranium.

In addition, the US is making progress with the development of gas centrifuge technology both with regard to design and centrifuge fabrication capacity. A pilot plant cascade known as the Component Test Facility (CTF) has begun initial operation. It is reported that the capacity of each individual centrifuge is several times that of centrifuges now being in use in European programmes, and that the production from CTF will soon exceed that of any other known centrifuge plant.

As a result of the government's desire to have the next increment of enrichment capacity built by private industry, Bechtel set up Uranium Enrichment Associates, an organization that was to build and operate a 9 million SWU per year gaseous diffusion plant. Three other companies (Exxon Nuclear, Electro-Nucleonics and Garrett Nuclear) have been preparing for the construction of centrifuge plants, each with a capacity of 3 million SWU per year. The absence of a decision on the matter has, however, delayed these projects. In November 1976, Bechtel announced that it would no longer actively pursue any role in uranium enrichment. Only when a decision on private or public ownership of uranium enrichment plants has been made can contracting for enrichment services from US sources be resumed.

Western Europe

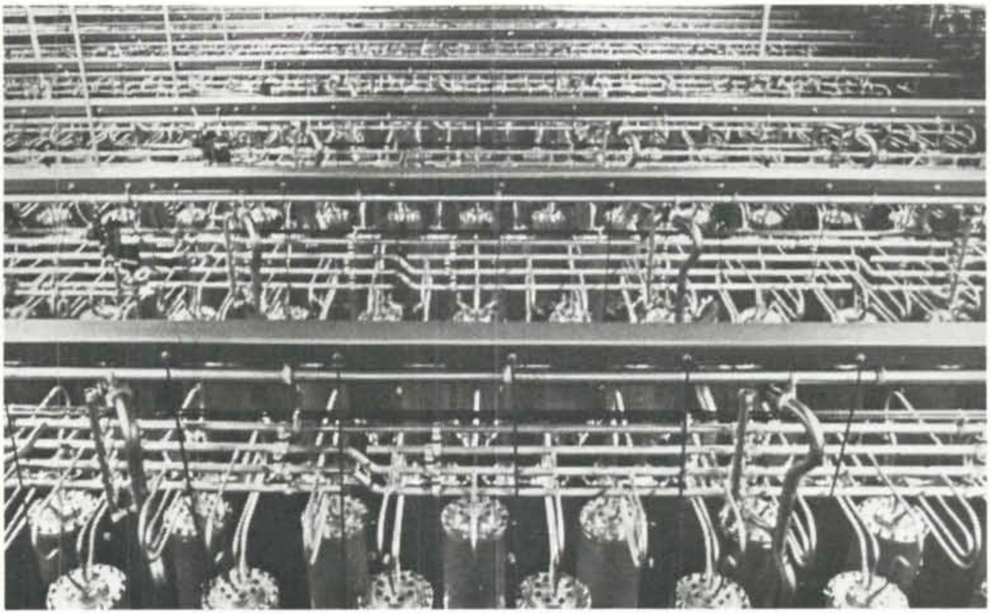
The large need for enrichment services in Western Europe combined with the long foreseen shortage of capacity in the USA and a European wish not to be entirely dependent on a single supplier have led to the construction of enrichment plants in Western Europe.

Diffusion process. This process was chosen by the EURODIF and COREDIF companies, which were established in 1972 and 1975 respectively. They have shareholders from Belgium, France, Iran, Italy and Spain but are headquartered in France. They selected the diffusion process because it is industrially mature and reliable, and has been used and developed on an industrial scale for 20 years in France. The French technology is different in design from the American technology. It had been developed and used for the operation of the Pierrelatte enrichment plant of about 500 000 SWU per year and forms the basis for EURODIF's Tricastin plant being built immediately south of the Pierrelatte plant in the Rhone valley. Start up is scheduled for December 1978 at 2.4 million SWU's per year capacity. The plant is to be completed and fully operational at a capacity of 10.8 million SWU by September 1981. The whole of the production is under contract until 1990, about 90% of it to the shareholders and the remaining to the Federal Republic of Germany, Japan and Switzerland.

The site for the next plant to be built by COREDIF has not yet been announced. The time-table for its construction will be adapted to meet the future demand for enrichment. It is planned that production would begin in 1983/84, reach 5 million SWU per year by 1985 and through successive increments reach the total annual capacity of 10 million SWU's. The flexibility of the production time-table will be obtained by integrating the operation of the COREDIF plant with the EURODIF plant. Contracts for the COREDIF capacity are now being proposed.

Centrifuge process. This process is new on the market. It was developed concurrently in the Federal Republic of Germany, the Netherlands and the UK. By the Almelo Agreements of 1970, the three Governments established technological and industrial co-operation on enrichment. This co-operation is executed by two companies (URENCO Ltd. and CENTEC GmbH) and two enterprises (URENCO UK and URENCO NEDERLAND). The two enterprises are responsible for design, construction, ownership and operation of centrifuge enrichment plants at Capenhurst in the UK and at Almelo in the Netherlands, respectively. A third enterprise in FGR is possible. URENCO provides a central marketing service while CENTEC co-ordinates the joint tripartite research and development programme. All companies have shareholders from all three participating countries.

Three pilot plants with a total capacity of 150 000 SWU per year are in operation, a Dutch plant and a German one at Almelo, Netherlands, and a British plant at Capenhurst, UK. Experience from these plants is being used for construction and operation of two production plants, one at Almelo and one at Capenhurst, which started operation in 1976 and will each be operating at full capacity of 200 000 SWU per year in 1978. URENCO will utilize the flexibility of the centrifuge process to progressively install further capacity to reach a total of 2 million SWU per year by 1982. Long-term contracts have been signed which fully utilize this capacity. An increase of capacity to 10 million SWU has been considered. This expansion is, however, dependent on the conclusion of future contracts, since URENCO is using the flexibility of the centrifuge process to expand capacity largely in step with the signature of new contracts.



Centrifuges in the German pilot plant at Almelo, Netherlands.

Centrifuges in the Dutch pilot plant at Almelo. Photos: URENCO.

USSR

The capacity of the uranium enrichment plants in the USSR is not known. They have been supplying enrichment services for the needs of the USSR and that of Eastern Europe. In addition, the USSR has concluded contracts for enrichment services with companies in Belgium, Finland, France, the Federal Republic of Germany, Spain and Sweden.

POTENTIAL SUPPLIERS

Countries with large resources of uranium ore, with a large potential for cheap hydro power, or with a large demand for enrichment services have an incentive to consider the construction of uranium enrichment plants.

Australia

Australia is interested in exporting the uranium from its large resources of uranium ore in an upgraded form, possibly as enriched uranium. It has been interested in the French diffusion process and is carrying out centrifuge research. There have also been contacts with Japan and URENCO. No decision regarding construction of a plant has been taken.

Brazil

A plant using the jet nozzle process is to be built in Brazil by a German consortium. Its capacity of 180 000 SWU per year is intended to supply Brazilian power reactors with enriched uranium fuel.

Canada

Like Australia, Canada intends to upgrade its resources of uranium ore as much as possible and therefore has considered the production of enriched uranium for export. There is a favourable hydro-electric power location and there have been contacts with American, European and Japanese companies and authorities. No final decision has been taken.

Japan

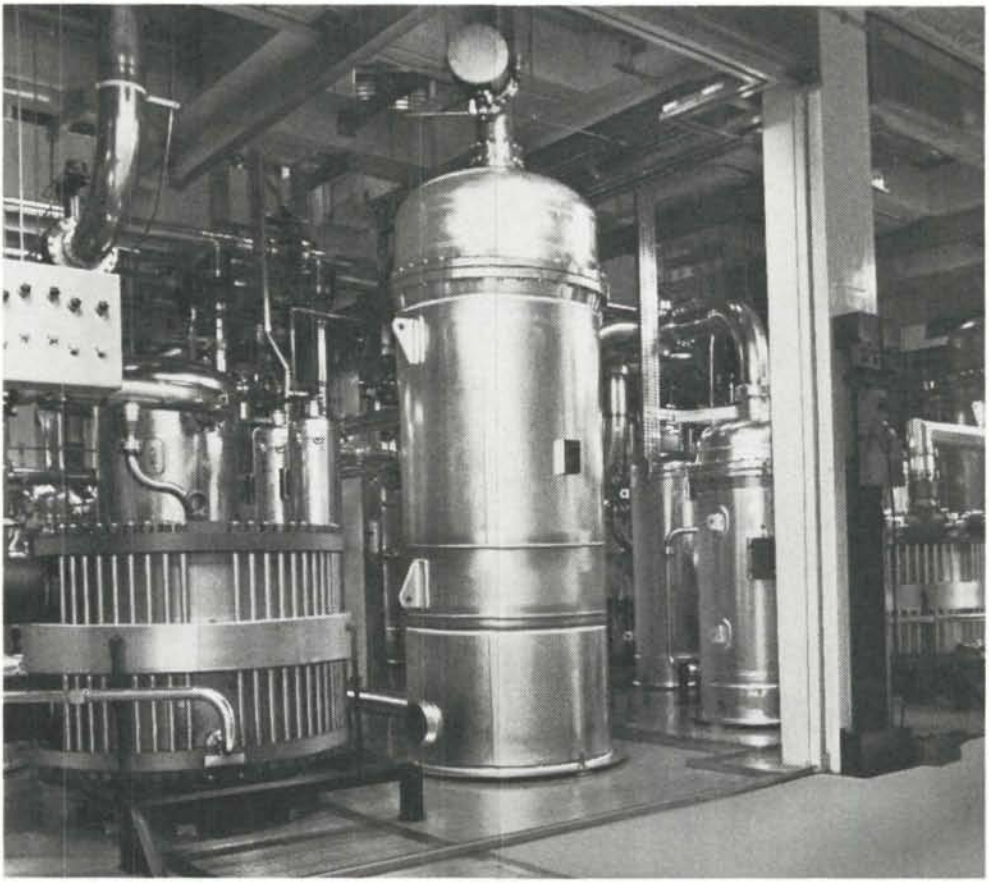
Japan's large enrichment requirements have encouraged it to work on the centrifuge process with a view of having a pilot plant in operation in 1980. The country has sufficient supply arrangements for enrichment services with ERDA and EURODIF into the 1990's. It has also explored the possibility of enrichment plants with Australia, Canada, South Africa, URENCO, and the USA.

CONCLUSION

There are no generally agreed data on the market for separative work. However, estimates of future requirements for uranium and nuclear fuel cycle services are published in Volume 18, number 5/6 of the *IAEA Bulletin*. This and other published information indicate that future requirements for separative work are now estimated at a considerable lower figure

Outside view of the uranium enrichment pilot plant at Valindaba, South Africa.

One of the cascade blocks in the Valindaba pilot plant for uranium enrichment. Photos: Uranium Enrichment Corp. of South Africa Ltd.



than only a year ago, and very much less than three years ago. This is primarily due to delays in completion of reactors definitely ordered and to reduction of new orders for nuclear power plants.

In the same period URENCO, EURODIF/COREDIF and the USSR have entered the market. In addition, it can be expected that the USA again will become a source of supply of separative work as soon as the basic decisions on ownership of enrichment plants have been taken.

The overall result is that the prevailing expectation in recent years of an imminent shortage of enrichment capacity has now diminished. Some observers of the market even estimate a temporary over-capacity in the 1980's if all enrichment plant projects are implemented as announced. Uranium enrichment plants have no customers other than nuclear power plants that use enriched uranium fuel, and the latter have no suppliers of enrichment services other than the uranium enrichment plants. This total interdependence between suppliers and users of enrichment services makes the developments now taking place on the enrichment market a matter which will be carefully watched by the parties concerned as well as by their governments.