ADVANCED ENRICHMENT TECHNIQUES

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ABSTRACT

BNFL is in a unique position in that it has commercial experience of diffusion enrichment, and of centrifuge enrichment through its associate company Urenco. In addition BNFL is developing laser enrichment techniques as part of a UK development programme in this area. The paper describes the development programme which led to the introduction of competitive centrifuge enrichment technology by Urenco and discusses the areas where improvements have and will continue to be made in the centrifuge process. It also describes the laser development programme currently being undertaken in the UK. The paper concludes by discussing the relative merits of the various methods of uranium enrichment, with particular reference to the enrichment market likely to obtain over the rest of the century.

INTRODUCTION

Several techniques can be used to enrich uranium. The two that have achieved industrial and economic maturity are gaseous diffusion, presently the production mainstay of the United States, France and the USSR, and the gas centrifuge used in the production plants of Urenco in the UK, the Federal Republic of Germany and The Netherlands. Figure 1 lists World Enrichment Plants. Other techniques being developed include chemical processes, aerodynamic processes such as the jet nozzle and the Helikon fixed-wall centrifuge, and laser isotope separation (LIS). The US Department of Energy (USDOE) and COGEMA in France have announced the expectation that LIS technology will, in the future, supersede their diffusion technology. Since both are now operating high-cost technology processes and are not in a position to compete with the second-generation technology of the centrifuge, such a decision to aim for a potential third-generation technology was to be expected.

Within BNFL advanced enrichment techniques are continually reviewed. BNFL is in a unique position in that it has industrial and commercial experience of diffusion enrichment and of centrifuge enrichment through its associate company Urenco, in which BNFL is a one-third shareholder. In addition following the generic work on LIS undertaken by the UK Atomic Energy Authority (UKAEA) from about 1974, BNFL initiated its own LIS development programme in 1982, aimed at the engineering concepts. In the middle of 1986 UKAEA and BNFL reviewed their programmes and are moving towards integrated development on a LIS programme extending into the mid 1990s and involving expenditure of several tens of £ million. From the assessment work so far it is not clear that laser enrichment will prove to be economically preferable to Urenco's advanced centrifuges.

Laser isotope separation is also being researched by BNFL's partners in the Urenco organisation, UCN (Netherlands) and Uranit (FRG). Any laser enrichment plant built by the Urenco partners would need to be competitive with the advanced gas centrifuges now under development. The laser work is being undertaken independently in each country with the partners being informed of progress. When or if a laser process offers economic advantages over centrifuges then it is planned that exploitation will be done jointly.

GASEOUS DIFFUSION

The UK's first diffusion plant started operating at Capenhurst in 1953. The high

Location	Owner	Type	Status	Capacity MSWU/y
Argentina	CNEA	Diffusion	Operating	0.02
Brazil	Nuclebras	Jet Nozzle	Under Construction	0.3
China-Lanzhou		Diffusion	Operating	0.08
France				
- Pierrelatte	CEA	Diffusion	Operating	0.3
- Tricastin	Eurodif (Marketed by COGEMA)	Diffusion	Operating	10.8
FRG - Karlsruhe	Steag	Jet Nozzle	Pilot	0.05
- Gronau	Urenco	Centrifuge	Operating	0.2 (1.0 by 1992)
Japan				
- Ningyo-Toge	PNC	Centrifuge	Pilot	0.05
		Centrifuge	Under Construction	0.2
- Shimokita	JNFI	Centrifuge	Planned	1.5
Netherlands				
- Almelo	Urenco	Centrifuge	Operating	1.0 (1.5 by 1991)
S. Africa				
- Valindaba	UCOR	Helikon	Under Construction	0.3
UK - Capenhurst	BNFL	Diffusion	Being Decommissioned	-
	Urenco	Centrifuge	Operating	0.7 (1.5 by 1993)
US - Oak Ridge	DOE	Diffusion	Standby	7.7
- Paducah	DOE	Diffusion	Operating)	19.5
- Portsmouth	DOE	Diffusion	Operating)	
USSR - Siberia	Techsnabexport	Diffusion	Operating	7 to 10 (3 generally offered to world market)

FIGURE 1 : World Enrichment Plants

enrichment section of the plant was closed in 1962 but the remainder continued in operation producing material for the UK AGR series of nuclear power stations until 1982. Now it is undergoing decommissioning and dismantling to remove all the diffusion enrichment equipment, including the eleven cooling towers.

The major disadvantages of the process are that it is very energy intensive and, because of the low stage separation factor, needs to be built in large scale units involving huge speculative investment. Nevertheless for operating plants, diffusion is still viable, especially when cheap electric power is available, although scope for real reductions in cost is limited, and with it the flexibility to respond to the likely continuing downward pressure on prices for the remainder of the century.

GAS CENTRIFUGE

Development work on the gas centrifuge process began at Capenhurst in the late 1960s with a pilot centrifuge plant starting operation in 1973. BNFL was one of the first organisations to develop the process on an industrial scale and brought its first centrifuge production plant on stream in increments from 1976. Since 1970 and the setting up of Urenco-Centec under the Treaty of Almelo, BNFL has collaborated with Dutch and German companies on the commercial development of the centrifuge process and plants are now being commissioned with a common type of machine. The joint development programme is being vigorously pursued to further reduce specific costs, increase output and therefore maintain Urenco's competitiveness in the enrichment market through the 1990s.

Background to Centrifuge Optimisation

In theory the maximum output of a centrifuge is proportional to its length and to the fourth power of its peripheral velocity although in practice a factor less than the fourth power operates, the value being influenced by the gas dynamics within the rotor. The velocity depends mainly on the materials chosen for rotor construction. The length depends not only on the materials but also on the dynamics of the rotor. For a given velocity and constraint on flexural resonance, length is proportional to diameter. Substantial development is therefore required to support a decision as to how much longer or faster to go in order to increase output.

The first stage is to confirm the broad selection of materials, diameter and length. The outline features then have to be formulated into a production design, suitable for building into a commercial plant. The ultimate objective is to operate many thousands of rotors in a plant continuously at high speeds for ten years and longer with no maintenance. This contrasts with the USDOE concept based on much larger machines which was cancelled in June 1985. USDOE accepted that its large machines would require in-service maintenance but the frequency of bearing failure appears to have been a serious drawback. Urenco centrifuge failure rates have been consistently better than the design assumption of 1% per year.

Progress in Centrifuge Development

Development of all the various centrifuge types installed in Urenco's plants has generally followed three phases : R&D, Qualification, Production. The R&D phase includes theoretical and design studies, materials testing, manufacture and spin testing of small numbers of components, and building and testing of typically 10 or 20 centrifuges. A period of two to three years is typical for this phase. The qualification phase has to prove that the centrifuge will operate successfully for up to 15 years under all plant design conditions. Manufacturing routes are established and demonstrated by producing typically 100 to 200 qualification centrifuges. The time for qualification is fairly constant, being typically three years. The production phase involves the increase in the manufacturing rates from the small pilot batch scale to the full production requirements of several thousands of machines per year. Tolerances are sometimes difficult to maintain and small design modifications often become necessary, backed up by proven mathematical models verified during qualification.

Figure 2 shows how centrifuge machine output has increased relative to the date of introduction into plant, together with current plans for future development. The reduction in plant specific capital cost as machine output increases can also be seen. The specific costs have been normalised to constant money values. It can be seen that specific cost will still be falling in the early to mid 90s. In fact, significant sums of money are already being spent annually on further advanced centrifuge concepts, scheduled for the mid to late 90s.

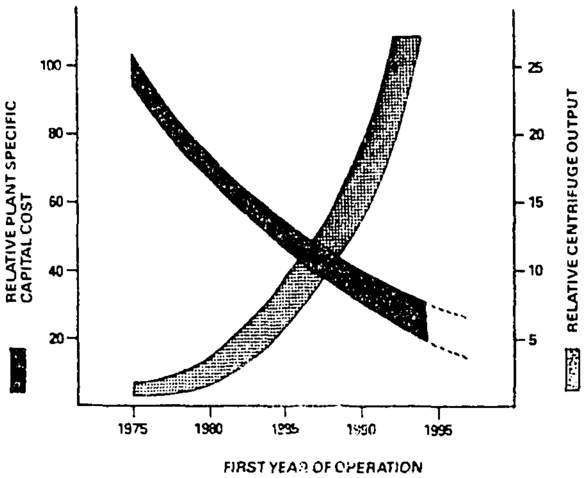

FIGURE 2: Normalised Specific Costs For Urenco Plants

Features of Gas Centrifuge Operation

The gas flow and separation characteristics of the centrifuges allow high efficiency cascades to be designed even for relatively small tranches of separative work (SW) capacity. A plant can therefore be extended in modular form and in each module the cascades can be closely approximated to the ideal shape for any specified low enrichment product concentration. The lead time for plant installation is short and the first useful product from a plant can be available two to three years after the investment decision. This together with the small unit size of plant increment has enabled Urenco to pursue a programme of capacity increase in phase with firm forward orders, providing a relatively stable and low-risk business environment enabling Urenco to establish a firm footing in the enrichment market. Power consumption is less than 10MW(e) for a 1 MSWU/y plant, which is less than 5% of that needed for an equivalent diffusion plant.

LASER ISOTOPE SEPARATION

In the UK, research on LIS has been proceeding since 1974 principally at UKAEA. The initial work there identified two laser-based processes that should be pursued. These were the molecular route based on UF_6 and the atomic route which uses elemental uranium vapour. Both routes were pursued, but with initial emphasis on the molecular route since the use of UF_6 as the working gas is well established in enrichment technology using both centrifuge and diffusion methods. This route was actively pursued until 1984 when from a detailed assessment of scientific progress and results, it was decided to place primary emphasis on the atomic route for scaling the technology towards plant size.

Principles of LIS

The principles of the molecular route are now well known. The UF_6 is cooled by expansion in a supersonic nozzle to reduce the vibrational temperature. Infra-red and ultra-violet laser photons are used to excite selectively and to dissociate the UF_6 molecules. The resulting UF_5, enriched in U-235 is a fine powder which can be removed from the UF_6 gas by filtration. Unfortunately the infra-red discrimination of isotopic species, which is excellent in experimental conditions, becomes too small as production conditions are approached. Furthermore, under production conditions the overall enrichment factors would prove too small for an economically viable single stage enrichment process to produce reactor fuel. Nevertheless, the relative ease with which UF_6 can be handled and the potential improvements in laser technology, particularly in the areas of energy density, pulse rates and reliability, mean that a watching brief needs to be kept on progress in this area. The FRG and Japan are both working on the molecular route.

The atomic vapour route (AVLIS) relies on th following three essential steps: production of a stream of atomic uranium vapour, using lasers to photo-ionise the U-235 selectively, and collection of the U-235 ions. The UKAEA work has confirmed that the uranium vaporisation process is understood and that suitable vapour streams can be generated. Studies of a three-photon ionisation process have enabled UKAEA to specify pulse energies, repetition rates and laser frequencies. A two-photon route was also studied, but at the present state of laser development, is considered less attractive. On the technological side, such aspects as beam quality, pointing stability and optical component quality have been studied. Finally a comprehensive analysis of various possible ion collection methods has been undertaken, and experimental systems built to test key aspects of preferred methods. All of the results of the UKAEA work have been made available to BNFL. AVLIS (SILVA) is regarded as the front runner in the French enrichment R&D programme while it is now the sole R&D option being pursued by USDOE.

Future Programme for UK LIS Development

BNFL initiated its own development programme in 1982, aimed at exploiting the engineering concepts of a commercially sized LIS plant. From the middle of 1986, UKAEA and BNFL have been pursuing an integrated development programme which will extend into the mid 1990s and will involve the expenditure of several tens of £ million. There will be five main areas for development: vapour production, laser light production, selective ionisation of U-235, separation and collection of tails and product, and engineering of a laser light facility.

BNFL has installed a test facility for evaporating uranium, which together with other equipment will be used for studying uranium vapour properties, electron-beam gun development and feed systems development. The copper vapour lasers which provide the light power needed for the process will continue to be developed for higher power and longer life. Spectroscopic work will be continued by UKAEA with the objective of finding energy levels which would enable U-235 to be ionised more efficiently. In addition work will be carried out on the light transmission characteristics of the envisaged systems. Techniques for the separation of the ions from uncharged atoms are being explored by the UKAEA. Application of these techniques to uranium vapour, and the subsequent product and tails collection and handling will also be investigated.

It is programmed that BNFL could be in a technical position to install a laser enrichment plant in the late 1990s. However, from assessment work so far, it is the present judgement of BNFL and others involved in the field that it will prove difficult for commercial enrichment by laser to achieve economic superiority over Urenco's advanced centrifuges before the end of this century. No early commitment to industrialization of the laser process therefore needs to be made by BNFL and a decision to install a laser plant or possibly a demonstration laser enrichment module is not required before the early 1990s. The LIS programmes of the Urenco partners are at the moment carried out separately in each country but they keep each other informed of progress, and when or if economic advantages of LIS are registered it is planned to exploit them jointly.

OTHER ENRICHMENT TECHNIQUES

The following techniques are included for completeness. None of them is believed to be able to compete with Urenco's advanced centrifuges. BNFL has done little more than retain a watching brief.

The French CHEMEX process is an example of chemical exchange. Such processes rely on the principle that a reversible chemical equilibrium, normally taking place between two phases, gives a small isotope separation. In CHEMEX two liquid phases, one organic and one aqueous, are allowed to interact inside large pulsed columns. The process has a reasonable enrichment factor, its energy consumption is low and its application requires only conventional techniques available in the chemical industry. However, early information suggested system residence times of 15 months to obtain 3% enrichment, implying a very large uranium inventory is needed.

The two most promising aerodynamic processes are the Becker Separation Nozzle and the stationary wall centrifuge or advanced vortex tube (Helikon) process. Separation by the Becker Nozzle is based on the centrifugal force of a curved jet comprising UF_6 and a light auxiliary gas to increase the jet velocity. The advantage is the capital cost which is potentially less than for centrifuge or LIS plants. However because of the repeated compression of large quantities of gas the power requirements are estimated to be up to 50% higher per SWU than for gaseous diffusion. Lower, but still high, energy consumption is a feature of the related South African Helikon process, which uses a mixture of UF_6 and H_2 as the process fluid. The process is based on tramsmitting streams of different isotopic concentrations without mixing by an axial-flow compressor, special cascading techniques being required.

Phase Equilibrium processes based on small volatility differences have been considered, but only fractional distillation of UF_6 is potentially viable and even then separation factors are not large enough to make it commercially attractive.

COMPARISON OF TECHNIQUES

From a technical point of view, separation factor is probably the most important aspect of any enrichment process. However, high throughput is required of a commercial plant and unfortunately for most processes separation factor is inversely proportional to the throughput rate. In-process inventory should not be too high for the process equilibrium time to be acceptable. Specific power requirements should be sufficiently low as to avoid excessive operating costs. From the simplified comparison on the attached table, which is essentially a technical evaluation, it is impossible to determine the 'best' enrichment process. This will be determined by market forces and the ability to provide the customer with enrichment at the right price at the right time.

THE ENRICHMENT MARKET TO 2000

The uranium enrichment market is extremely competitive. Present capacity greatly exceeds demand and indeed demand is unlikely to reach even current installed capacity until about the turn of the century, as shown in Figure 3. In this situation there is

Units MSWU				
Requirements *	1987	1990	1995	2000
- Committed	24	26	23	20
- Not Committed	-	-	6	13
TOTAL	24	26	29	33
Capacities	36	37	39	41
Excess Capacity	12	11	10	8

FIGURE 3: ENRICHMENT REQUIREMENTS AND CAPACITIES (WORLD OUTSIDE COMMUNIST AREAS)

* Requirements are based on 0.25% tails and allow for SW stock run-down.

inevitably a continuing downward pressure on prices and this will be perpetuated for at least the remainder of the century. The development potential of the Urenco gas centrifuge, for example in terms of advanced materials and improved bearings and rotor systems, means that this technology will remain competitive throughout the 1990s, as prices fall, since production costs will be reduced as shown in Figure 2.

USDOE have for some time recognised the pressure of prices and their competitors' abilities to respond and in mid-1985 prepared a strategy document including the familiar price projections graph. To approach their price target curve, USDOE examined several options and decided upon a two phased pricing structure and subsequent deployment of an AVLIS plant, from about 1995. The French are probably in a similar situation to USDOE and they recognise that modular units are likely to facilitate progressive penetration of LIS technology and that existing diffusion plants will not be displaced before the turn of the century.

The other major supplier to the enrichment market, Techsnabexport, has in the past appeared to offer discount prices against those which a customer has received from its usual supplier. With the likely downward trend on prices the fact that high-cost diffusion technology is being used may make this method of obtaining foreign exchange less attractive.

Other Market Forces

Increasing quantities of the uranium to be enriched during the 1990s will arise from reprocessing. The enrichment of uranium derived from the spent Magnox fuel generated in the UK is now becoming a routine matter for Urenco and much of the product is already in use in the UK's Advanced Gas Cooled Reactors. During the 1990s approximately 25,000 t of uranium is expected to arise worldwide from the reprocessing of spent oxide reactor fuel, BNFL's THORP plant at Sellafield providing a substantial part. BNFL are planning a hex conversion plant for reprocessed material at Springfields, to be on-line in the early 1990s.

Re-enrichment is possible in diffusion plants using campaigning or dilution. Segregation of batches within campaigns however is not generally practicable and because of the large process hold-up significant quantities of 'rainbow' material arise at the start and end of campaigns. With dilution the economic penalties associated with U-236 contamination are shared among all customers whether or not they have provided reprocessed feed. Urenco's centrifuge technology offers significant advantages because of the modular nature of the plant. Reprocessed material can be segregated into a particular operational unit preventing cross-contamination with other customers' natural uranium and enabling the minor radiation hazard to be better controlled, and/or campaigning can be performed very effectively because of the low in-process inventory. Furthermore, the no-maintenance concept means very low operator exposure. Laser separation may offer the advantage of being able to avoid the enrichment of the minor uranium isotopes with a consequent increase in the economic worth of the product but the full implications of this method of enriching reprocessed uranium have not been assessed. What is certain is that no inroads into the likely stocks of such material will be made by the laser process in this century.

Adoption of AVLIS will have implications on the fuel cycle because of its metal feed and product. BNFL as a company engaged in providing a complete nuclear fuel cycle service is in a good position to make a full assessment of the commercial implications. BNFL has an established uranium metal manufacturing capability and is already developing a dry route (complementary to its world-renowned integrated dry route, IDR) for conversion of enriched metal to ceramic oxide.

CONCLUSIONS

The development potential of the diffusion process has been exhausted and little scope for economic improvement remains. The gas centrifuge has significant potential for specific cost reductions through the 1990s and will be able to respond to market trends during that period. Of all the other enrichment techniques laser isotope separation is the most promising because of its potentially low costs and high separation factors. The technology, however, has yet to be demonstrated on an industrial scale and the timescale on which it can be implemented commercially must be uncertain. For that reason BNFL and its Urenco partners are continuing with their forward investment plans based on centrifuge technology but maintaining active laser development programmes, with the aim of being able to install a plant, if commercially viable, by about the turn of the century. The decision to install such a plant is not required during this decade.

TABLE COMPARISON OF ENRICHMENT PROCESSES

Process	Status	Stage Enrichment	Throughput	Process Pressures	Inventory	Power Usage	Specific Costs	
							Capital	Operating
Gaseous diffusion	Mature. Little room for improvement	Low	High	Moderate	High	High	High	High
Gas centrifuge	Substantial growth potential. Commercially proven	High	Low	Low	Low	Low	Moderate	Low
Laser enrichment	Fundamental R&D stage. Substantial development required	Very High	Very Low	Very Low	Low	Very Low	Low (F)	Low (F)
Chemical exchange	Laboratory Stage. Yet to be commercially proven	Moderate	High	Low	High	Low	Very High	Moderate
Phase Equilibrium	Not Commercially Attractive	Very Low	High	Low	High	High	High	Very High
Aerodynamic Processes	Semi-Commercial Plants Under Construction. Not yet proven	Moderate	Moderate	Moderate	Low	High	Low (F)	Very High

(F) = Forecast

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V. S. Crocker (UKAEA) and P. F. P. Roberts (BNFL) "Development and Policy Implications of Laser Isotope Separation in the UK", Uranium Institute, London (4 September 1986).