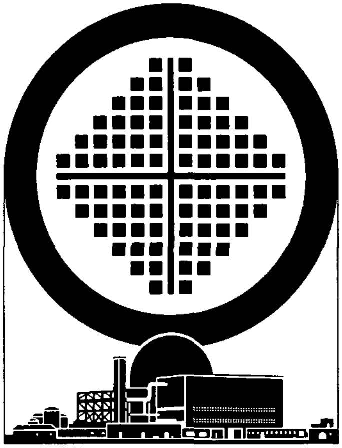

URANIUM ENRICHMENT:

Supply, Demand and Costs

by J. Tom Roberts,

Most of the proven reactor types envisaged for commercial operation over the next two decades require enriched uranium. Even assuming a larger share for natural uranium fueled heavy water systems and an early date of introduction for breeders on a commercial scale, enriched uranium fueled stations are likely to represent the bulk of the new nuclear capacity to be installed between now and the turn of the century. Hence the problem of ensuring an adequate supply of enrichment services at the lowest possible cost is just as important as that of securing a solid basis of uranium ore reserves. The present enrichment capacity available in the western world is likely to be exhausted in the early 1980's, the exact date depending on the rate of growth of nuclear capacity and on plausible variations in the proportions of different reactor types. Since the lead time between consideration and commissioning of an enrichment plant is of the order of 8 to 10 years, and since the issue has significant national, regional and international aspects on the commercial and political levels, it has recently been in the forefront of interest, and no review of nuclear power prospects would be complete without its consideration.

DEMAND AND SUPPLY

The demand for separative work depends on the demand for enriched uranium, on the enrichment levels of the fuel and of the enrichment plant tails. The demand for enriched uranium is in turn determined by the nuclear power demand, the reactor strategy, reactor characteristics, capacity factor, delay times, and plutonium recycle policy.

Dependence on Nuclear Power Growth Rate and Reactor Strategy*

Figure 1 shows the range of annual separative work requirements to 1990 calculated for various nuclear strategies with different reactor mixes based on 0.25% U-235 tails assay and with no allowance for plutonium recycle. The demand is seen to depend more on the nuclear power growth rate than on the particular reactor strategy adopted. For the medium nuclear power growth cases, the separative work requirements increase from about 10 000 tonne units/year at present to about 90 000 - 110 000 by 1990. The overall range of the 1990 projections including the low and high nuclear power growth cases, is about 70 000 - 130 000 tonne units/year.

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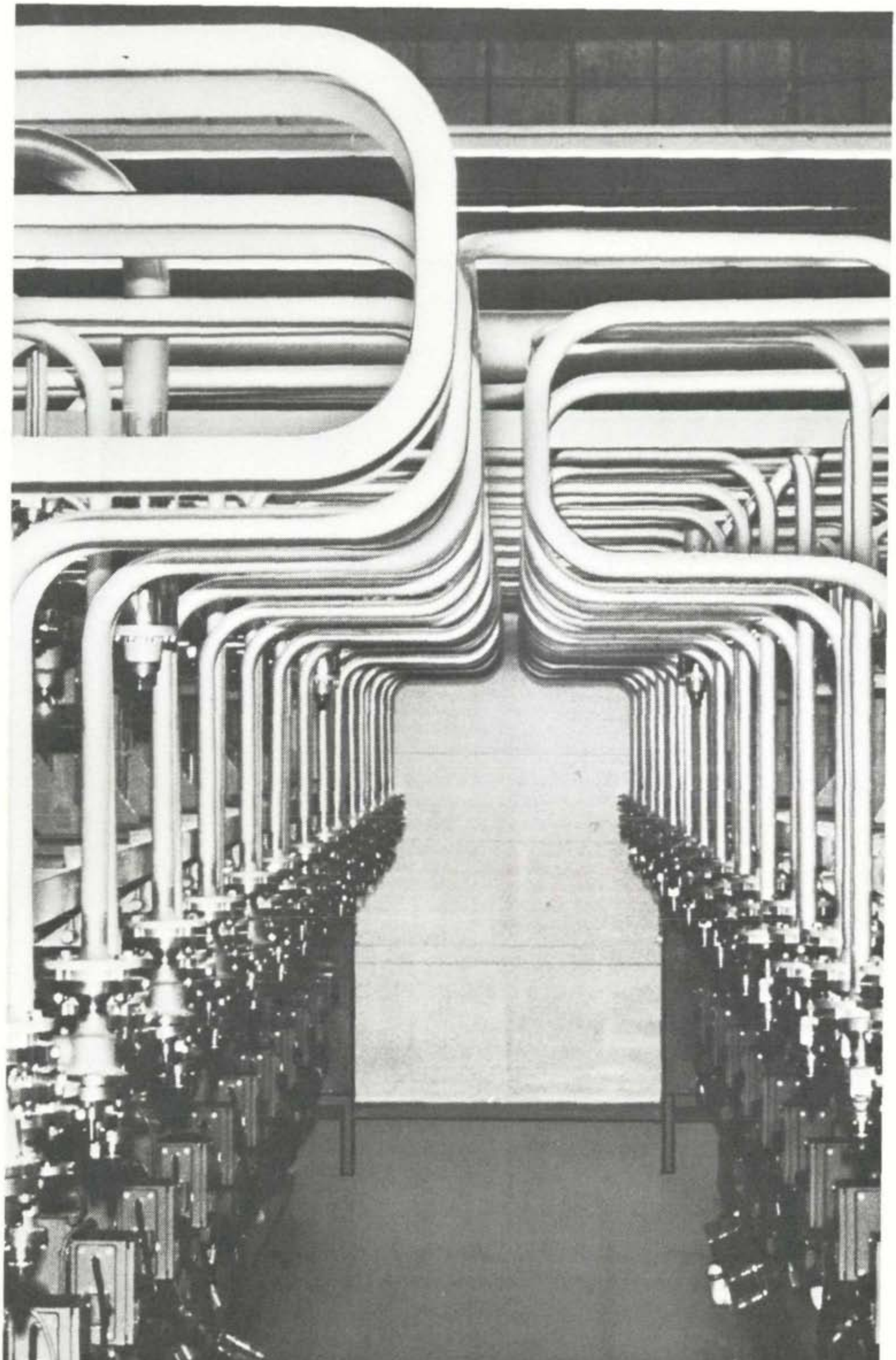
* A large part of the information presented here is based on the results of the joint study on uranium supply production and demand jointly prepared by the OECD-NEA and the IAEA, and expected to be published in September 1973.

The German uranium enrichment pilot plant UTA 25 in Almelo, Netherlands.
This photo, taken in January this year, shows the cascade pipes during the first stage of construction. ▶



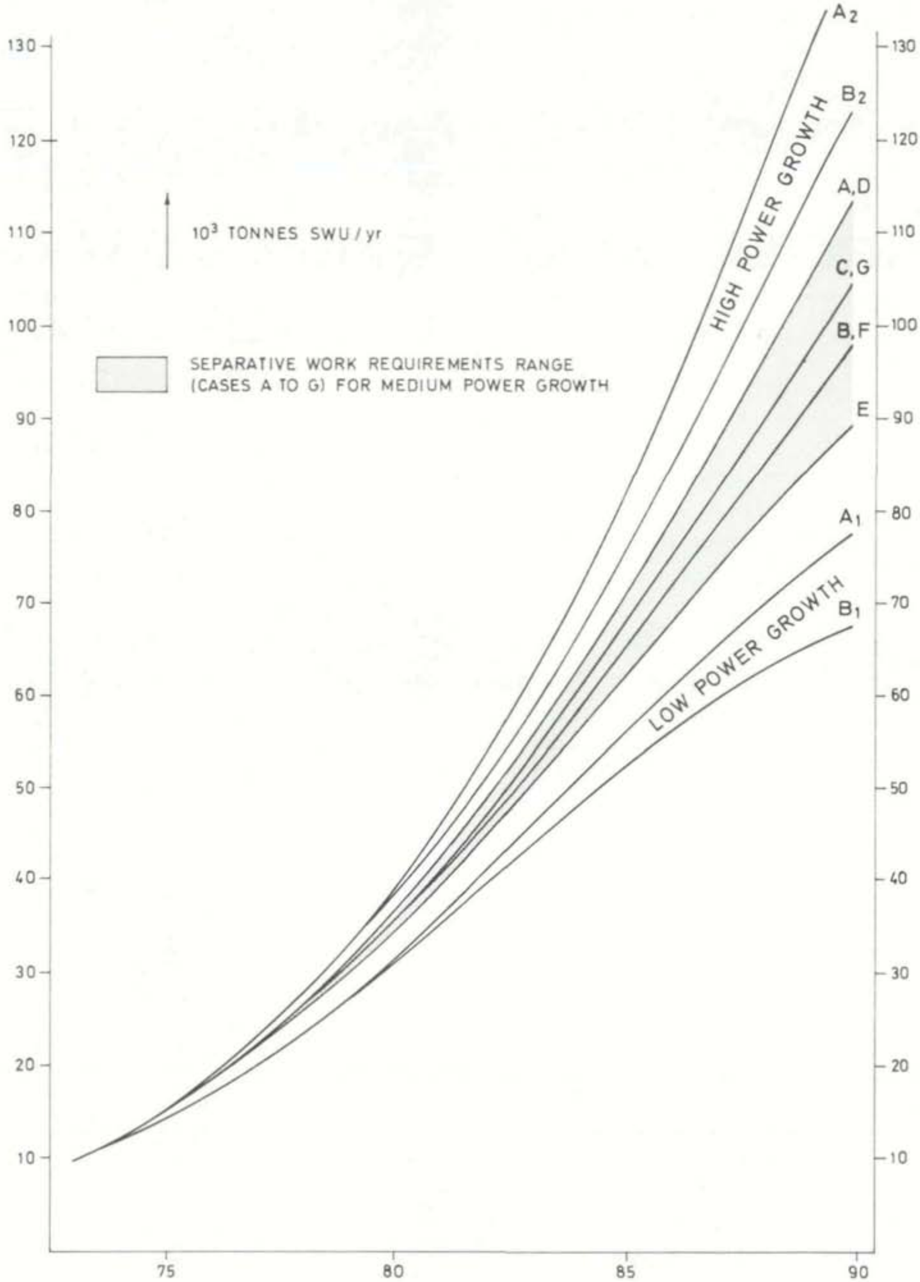


Figure 1. Annual Separative Work Requirements for Different Reactor Strategies and Power Growth (no Pu recycle, 0.25% tails assay).

For the medium nuclear power growth cases (A through G) it can be seen that the separative work demand does not depend significantly on high temperature reactor strategy (e.g. case A with a low high temperature reactor growth and case D which differs only in that it has high HTR growth; both have essentially the same separative work requirements). On the other hand, changing from low to high fast breeder reactors (e.g. case A to case B) reduces 1990 demand by about 15%, while changing from low to high HWR growth (e.g. case A to case C) reduces it by about 8%. (Beyond 1990 the effect of following a high growth strategy would become increasingly significant.)

Table 1 shows the annual separative work requirement and the cumulative requirements for each year from 1973 to 1990 for cases A (continuation of present trend), B (like A except with high rate of FBR introduction), A_2 (highest separative work requirements of 15 cases considered) and case B_1 (lowest requirements). Table 1 is based on 0.275% tails assay and on plutonium recycle starting in 1978, whereas Figure 1 is based on 0.25% tails assay and no plutonium recycling. These changes have reduced the 1990 demand by about 15% for case A but only about 6% for case B, i.e., the demand is less sensitive to FBR growth.

TABLE 1. ANNUAL WORLD SEPARATIVE WORK REQUIREMENTS IN 10^3 TONNES SWU/YR
(0.275% tails assay, Pu recycle)

Year	Lower Limit Case B_1 *		Medium Range Case B*		Medium Range Case A*		Higher Limit Case A_2 *	
	Annual	Cumulative	Annual	Cumulative	Annual	Cumulative	Annual	Cumulative
1973	9	9	9	9	9	9	9	9
1974	10	19	11	20	11	20	11	20
1975	13	32	14	34	14	34	14	34
1976	16	48	17	51	17	51	18	52
1977	18	66	20	71	20	71	22	74
1978	21	87	24	95	24	95	26	100
1979	23	110	26	121	26	121	29	129
1980	26	136	30	151	31	152	33	162
1981	30	166	35	186	35	187	39	201
1982	34	200	40	226	41	228	46	247
1983	37	237	45	271	46	274	52	299
1984	41	278	51	322	52	326	60	359
1985	45	323	57	379	58	384	68	427
1986	48	371	63	442	65	449	78	505
1987	51	422	70	512	73	522	88	593
1988	56	478	77	589	81	603	99	692
1989	59	537	85	674	89	692	111	803
1990	61	598	91	765	97	789	124	927

* B with high breeder component   * A with low breeder component

TABLE 2. PROJECTED DIFFUSION PLANT POWER LEVELS AND SEPARATIVE WORK AVAILABLE VERSUS SEPARATIVE WORK REQUIRED ASSUMING "MOST LIKELY" NUCLEAR POWER GROWTH
(Separative Work in Millions of SWU)

	FY 1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
DIFFUSION PLANT OPERATIONS													
Operating Tails Assay (Percent U-235)	0.30	0.30	0.30	0.30	0.30	0.275	0.275	0.275	0.30	0.30	0.30	0.30	0.30
Average 3-Site Power Level (Megawatts)	4069	4558	5008	5567	5733	6199	6788	7110	7110	7178	7380	7380	7380
Annual Separative Work Production	12.7	14.2	15.7	18.0	19.8	22.5	25.4	26.9	26.9	27.2	27.7	27.7	27.7
Included Separative Work:													
From CIP			0.6	1.9	3.4	4.4	5.4	5.7	5.7	5.7	5.8	5.8	5.8
From CUP						0.9	2.9	4.0	4.0	4.2	4.7	4.7	4.7
SEPARATIVE WORK SUPPLY AND DEMAND (0.30 PERCENT TAILS ASSAY)													
Effective Annual Increment in Separative Work Available due to 0.30 Percent Tails Recycle and Evaluation at 0.30 Percent Tails Assay						(1.7)	(1.9)	(1.4)					
Cumulative Separative Work Available Including the July 1, 1973, Inventory of 17.1 Thousands of Units	29.8	44.0	59.7	77.7	97.5	118.3	141.8	167.3	194.2	221.4	249.1	276.8	304.5
Annual Separative Work Required[1]	12.7	8.3	12.2	15.5	15.1	21.3	26.4	30.4	34.9	45.9[2]	42.8[2]	46.6[2]	53.2[2]
Cumulative Separative Work Required	12.7	21.0	33.2	48.7	63.8	85.1	111.5	141.9	176.8	222.7	265.5	312.1	365.3
Separative Work in Preproduction Inventories	17.1	23.0	26.5	29.0	33.7	33.2	30.3	25.4	17.4				
Separative Work Required from New Plant:													
Annual										1.3	15.1	18.9	25.5
Cumulative										1.3	16.4	35.3	60.8

[1] Covers projected domestic and foreign central station power demand, Government and other nonpower applications. Adjusted for advance sale of separative work to the Japanese.

[2] Separative work required includes a flywheel equivalent to 1/6th of the next years requirements. The flywheel requirement is 7.1 in FY1983, 0.5 in FY1984, 1.1 in FY 1985, and 1.0 in FY 1986.

Comparison of Demand and Supply

Table 2 shows the July 1973 USAEC projection of separative work supply from the three US gaseous diffusion plants, increasing to 27 700 tonne units including the added capacity from the cascade improvement programme (CIP) and the cascade uprating programme (CUP). It shows the cumulative separative work available (including inventory on hand at the beginning of fiscal-year 1973). It also shows the estimated annual and cumulative separative work requirements through 1986, the USAEC estimates being not very different from case B of Table 1 (considering that Table 1 is on a calendar-year basis and Table 2 on a fiscal-year basis, starting six months earlier than the calendar year). Table 2 then shows the separative work inventory, or stock (from pre-production of enriched uranium, i.e. before it is actually needed) increasing to a maximum in 1978 and declining to zero by fiscal-1983, and the corresponding need for increasing amounts of new capacity in 1983-1986.

Table 3 shows existing and planned separative work capacity in Western Europe, indicating 10 000 tonne units of annual capacity by 1985. Not included because of lack of precise information are other plans for new enrichment capacity inside and outside the USA, although recently published information indicates that substantial capacity is available in the USSR. Also, Eurodif is studying a French proposal for a large gaseous diffusion plant which could have a starting capacity of 5000 tonne units, increasing to 9000 at the beginning of the 1980's; and the Republic of South Africa has announced its intention of building an enrichment plant using an undisclosed separation process.

TABLE 3. EXISTING AND PLANNED* SW PRODUCTION CAPACITY IN EUROPE
(10^3 tonnes SWU)

	1973	1975	1980	1985
Urenco**	50	400	2000/3000	10000
CEA France, Pierrelatte	200			
UKAEA, Capenhurst	400			

* Information obtained at Colloquium on Uranium Enrichment Technology at Nuclex 72, Basel

** Adjusted due to recent announcements (see N.W. 22nd March, 1973).

Figure 2 shows the annual production of separative work in USA (from Table 2) and Europe (from Table 3) and the additional capacity needed considering the requirements of the four cases of Table 2. For the high-demand case additional capacity is shown to be needed by 1982, for the likely-demand case by 1983, and for the low-demand case by 1987. **Figure 3** shows the same information in terms of the separative work stock (inventory), showing it increasing to a maximum and then falling to zero by 1981-1986, depending on which nuclear power demand case is assumed.

Figure 4 shows that USA requirements will exceed presently-planned USA supply by 1985, for case A, and then will almost double by 1990. It also shows that projected demand outside the USA is essentially equal to the projected USA demand, whereas presently contemplated European supply is much lower than that of the USA.

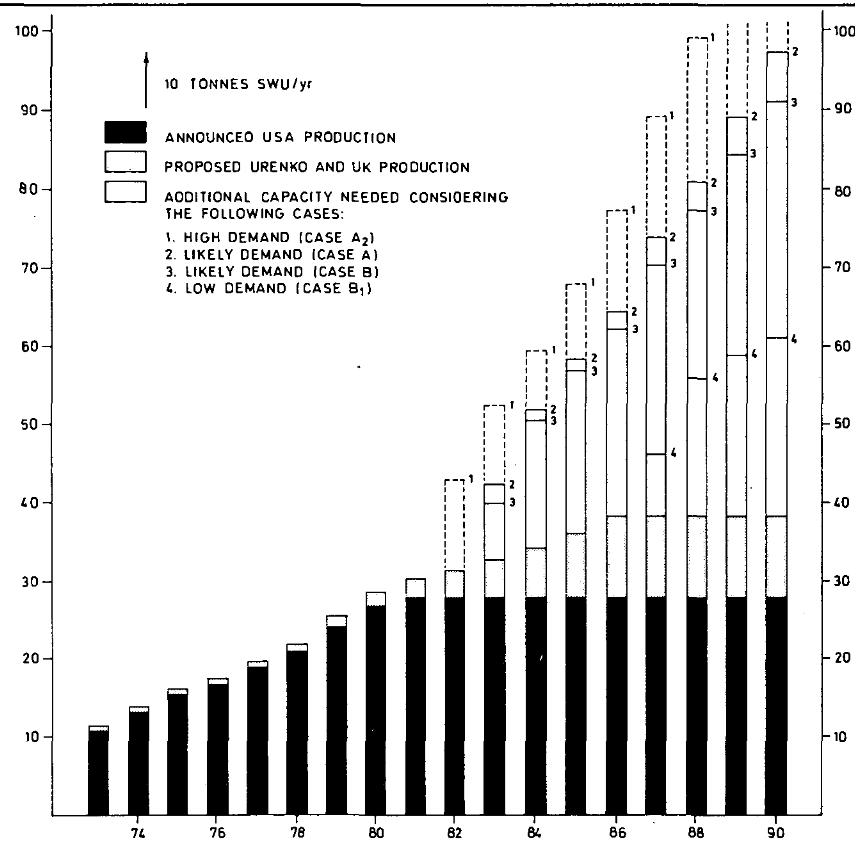


Figure 2. Annual Separative Work Production and Additional Capacity Needed (0.275% tails assay and Pu recycle).

Figure 5 shows the sensitivity of projected separative work demand to assumed tails assay, for no plutonium recycle. By comparison with Figure 1, for 0.25%, it indicates that increasing the tails assay to 0.30% would decrease 1990 demand by about 10%.

Uncertainties in the supply situation as presented above include any excess of enrichment capacity over requirements in the countries not included (USSR, Eastern Europe, China, South Africa) and possible use of military stockpiles of enriched uranium and plutonium.

COSTS

Past and Current Costs

The USAEC, which has supplied most of the commercial separative work to date, has increased its prices per kilogram unit from $26.00 to $28.70 in 1970, to $32.00 in 1971 and to $36.00 to $38.00 (depending on type of contract) in 1973. The prices for sales from other sources (e.g. USSR and France) have not been announced.

The current USAEC prices understate actual costs somewhat because of the requirement of contracting for requirements eight years in advance, with penalties for cancellation, and because partial advance payments are required. Also, the effective current cost to

Figure 3. Separative Work Stock resulting from URENCO-, UK- and US production (0.275% tails assay with Pu recycle).

Figure 4. Annual Separative Work, Requirements and Production (0.275% tails assay, Pu recycling).

Figure 5. Annual Separative Work Demand for Different Enrichment Tails Assays (no Pu recycle).

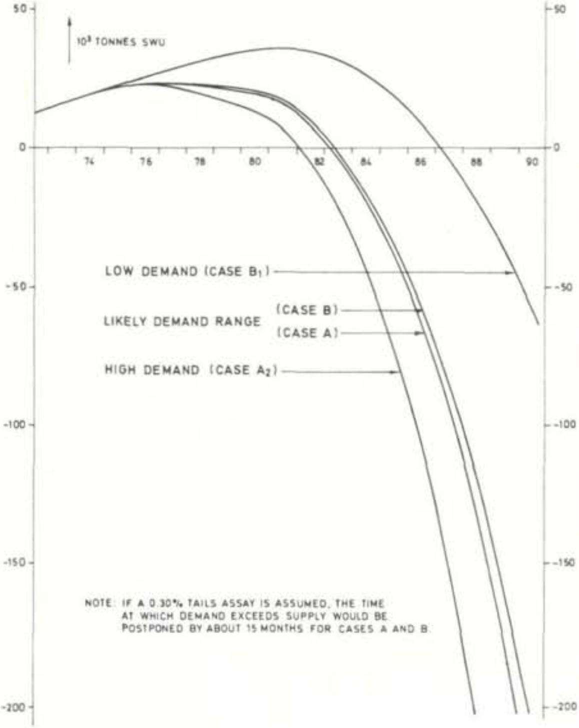
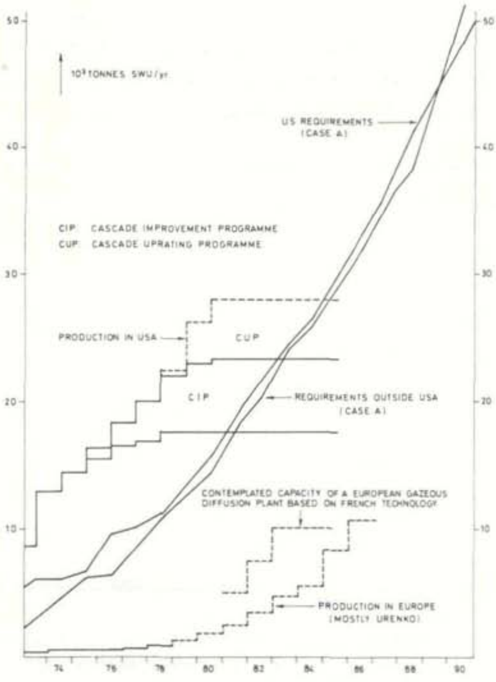


Figure 3 ▶



▲ Figure 4

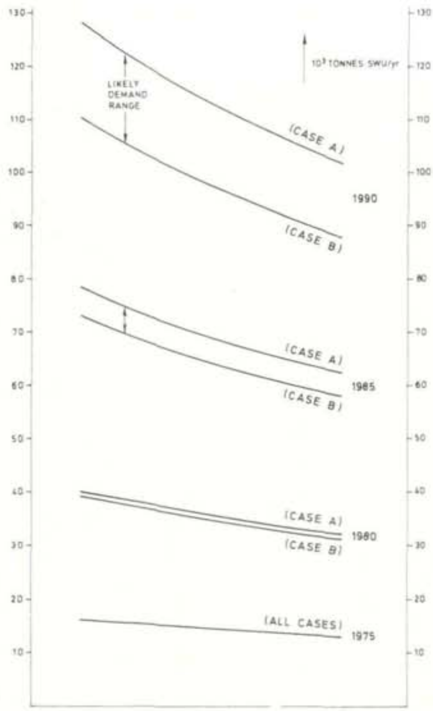


Figure 5 ▶

the customer is increased slightly by the USAEC policy of calculating natural uranium requirements and separative work charges on the basis of 0.20% U-235 tails assay, rather than on the 0.30% actual operating level or on a tails assay chosen by the customer. For an "ideal" enrichment cascade the relationship between cost of enriched product and its enrichment level is such that there is an "optimum" value of tails assay which increases with increasing cost of separative work and decreases with increasing cost of natural uranium hexafluoride. For the current cost levels of these two items the optimum tails assay lies between 0.25 and 0.30%. For enriched uranium in the 2.2% - 2.6% U-235 range, the USAEC policy results in a combined cost of natural uranium plus enrichment about 3% higher compared to the optimum policy.

Future Costs

Until now predicting the future cost of separative work has been rather speculative, since the USAEC has raised its prices over the past few years at a fairly rapid rate and has had relatively little competition. Very recently, however, URENCO has announced that it is prepared to enter into contracts for uranium enrichment at $48.00 per kg unit, with a four-year advance commitment. This is a higher price than the current USAEC price, though not necessarily higher than would be charged by a new privately-owned plant in the USA (as discussed below).

Costs for gaseous diffusion separative work are sensitive to both capital costs and operating costs, the latter being dominated by electric power costs. Centrifuge plants are expected to consume only about 10% as much electric energy as gaseous diffusion plants of comparable capacity, though their other operating costs are expected to be higher.

Table 4 shows the latest USAEC estimates of capital costs and operating costs (excluding electric power costs) for gaseous diffusion and centrifuge plants. The capital costs for the two competitive processes are estimated to fall in the same range, though a gas centrifuge plant is estimated to have much higher non-power operating costs.

TABLE 4. SUMMARY OF ENRICHMENT PLANT ESTIMATES
(8.75 Million SWU/Year Plant at a New Site FY 1974 Dollars)

	Gaseous Diffusion Plant		
	CIP Technology	Advanced Technology	Gas Centrifuge Plant Range of Costs
Capital Cost, Million $	1,400	1,200	1130 - 1710
Specific Investment, $/SWU	160	137	129 - 195
Operating Cost (except power) Million $/Year	16	16	70 - 115

A gaseous diffusion plant of 8.75 million SWU capacity requires about 2400 megawatts of electric power. A gas centrifuge plant of that same capacity requires substantially less power, within about 10% of that power.

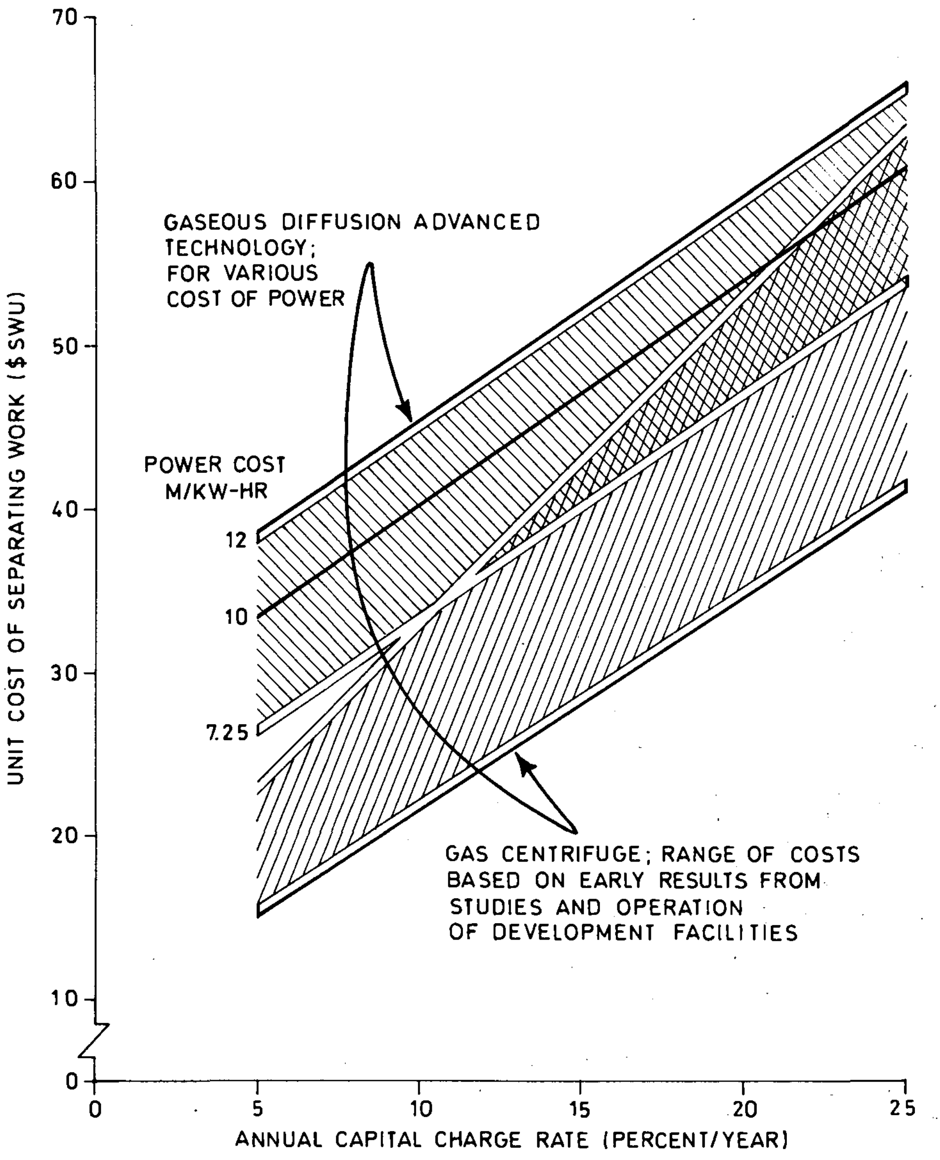


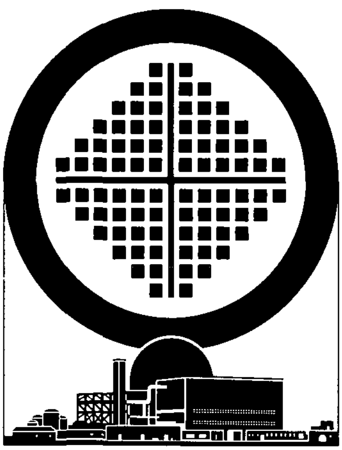
Figure 6. Comparison of technologies 8.75 million SWU/year plant at a new site.

Figure 6 shows the latest USAEC estimates of unit separative work cost range for gaseous diffusion and centrifuge plants, as a function of power cost and annual capital charge rate. At low capital charge rates (under 10%/year) centrifuge plants have a clear advantage; however, at the higher capital charge rates typical of private ownership gaseous diffusion is indicated to be competitive and is considered to be less risky since the technology is considered to be well demonstrated.

Expansion Decision Timing

The USAEC has recently estimated that the time from process decision date to equivalent full production date is approximately seven years for either gaseous diffusion or centrifuge plants, the latter having a somewhat shorter construction time but a longer start-up time. The URENCO requirement of only four years advance commitment in supply contracts implies that they estimate only about four years lead time for planning capacity expansion.

It should be observed that since gaseous diffusion plants require large increments of electricity generation, their lead time cannot be less than that required to build the associated electric power plants. Centrifuge plants, having much smaller power requirements, are not necessarily subject to this limitation.



The Need for Fast Breeder Reactors

by R. Skjoeldebrand

The preceding articles in this issue have shown that the world for many decades to come will have to rely to an ever increasing extent on nuclear energy to meet the demands for primary energy. To meet these requirements we must, however, have a reactor type with lower needs for uranium and also enrichment services, which otherwise may place a limitation on how far nuclear energy can be used. The breeder reactor, with its ability to convert uranium 238 into fissile plutonium, is a solution and would indeed offer a practically inexhaustible source of energy from uranium for centuries to come. The basic reason is that the very much higher utilization of the uranium in a breeder reactor (more than 60 times higher than in a light water reactor) permits the use of uranium of much higher initial price, and the available reserves multiply as a consequence.

Several countries have over many years devoted a considerable part of the nuclear energy programmes to breeder development and the first six medium-sized demonstration plants are now either already in the early stages of operation or under construction. All are of the same basic type, i.e. the liquid metal cooled fast breeder, although the alternatives, e.g. a gas cooled breeder, would have been possible and could have offered some advantages. These programmes are extremely costly and it has been estimated that development of a first commercial prototype will require a total cost of at least \$2000 - \$3000 million; each programme occupies several thousand scientists in government laboratories and in industry.