# THE ECONOMICS OF URANIUM ENRICHMENT

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*A number of factors which determine the demand for enrichment services are identified and projections of enrichment capacity and requirements to the year 2000 are discussed. An outline of the nuclear fuel cycle is given. The prospects for the establishment of an Australian enrichment supply industry during the 1990s are considered. It is concluded that those prospects are limited by the depressed state of the world market and the lack of a domestic market.*

## INTRODUCTION

On current projections, about 90 per cent of all uranium required over the period to the year 2000 will have to be enriched. The guaranteed supply of enrichment services, therefore, is of critical importance to nations who rely on nuclear power as their major source of electricity. The provision of enrichment services, however, entails the construction of expensive plants using classified technology and, for plants using the diffusion process, the provision of considerable supplies of power. The enrichment stage of the nuclear fuel cycle accounts for nearly 50 per cent of the total cost, excluding costs associated with the power plant itself. The other major cost is that of the raw material, yellowcake ($U_3O_8$). The costs associated with conversion, fuel fabrication, and spent fuel storage, transport and disposal are all relatively minor.

In this paper, a number of factors which determine the demand for enrichment services are identified, and projections of enrichment capacity and requirements to the year 2000 are discussed. By way of background information, an outline of the nuclear fuel cycle is given in the next section prior to the economic analysis. The concluding section of the paper discusses the prospects for the establishment of an Australian enrichment supply industry during the 1990s.

## THE NUCLEAR FUEL CYCLE

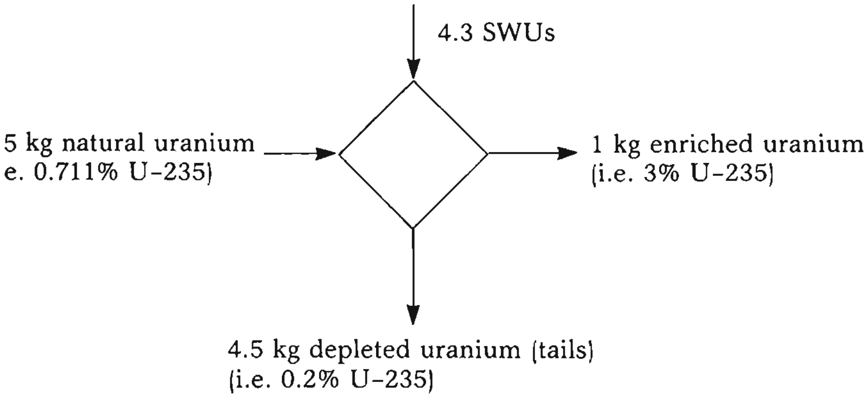
Mining uranium ore is the first in a series of steps known as the nuclear fuel cycle. The mined ore is sent to a mill where uranium concentrate ('yellowcake') is produced. The majority (about 75 per cent) of nuclear reactors currently in operation require that the uranium be 'enriched' before it can be used as fuel. Natural uranium contains 0.7 per cent of the energy producing 'fissile' U-235 isotope of uranium. The remainder of the natural uranium, U-238, is the 'non-fissile' part. Simply stated, uranium enrichment is the process by which natural uranium is physically altered into a richer mixture of the fissile isotope U-235, which can then be used as fuel in nuclear power reactors to produce electricity. Enrichment requires that the uranium concentrate first be converted into uranium hexafluoride. Uranium conversion and enrichment plants are in commercial operation in the USA, USSR and Western Europe. Because uranium enriched to very high levels can be used in nuclear weapons, uranium enrichment technology is 'classified' and all enrichment agencies are government controlled.

The enriched material is shipped to a fuel fabrication plant where it is converted to uranium dioxide, formed into pellets and placed in zirconium tubes. The tubes are assembled into bundles, called 'fuel assemblies', and sent to nuclear power plants. The fuel assembly is inserted into the power reactor where the fuel is used to generate heat through the process of fission. From this point on, the system follows the conventional steps of using the heat to produce steam, which in turn drives steam turbines that turn electric generators.

After the fuel has been used in the nuclear reactor, it is discharged and cooled. Most spent fuel is currently stored on reactor sites, but it is possible to recover and reprocess any residual uranium and the reactor produced plutonium for re-use in the fuel cycle. The remaining waste products are highly radioactive and would have to be shipped to a permanent storage repository. Commercial reprocessing is currently at the pilot plant stage in many countries, and the economic viability of such projects is uncertain. Reprocessing of spent fuel can substantially reduce the amount of 'new' uranium required by the nuclear power industry.

## ENRICHMENT SERVICES

Uranium enrichment services are sold in separative work units (SWUs), which are a measure of the amount of effort required to separate U-235 from U-238. The proportion of U-235 remaining in the depleted uranium (the tails) after enrichment is called the tails assay. In order to produce 1 kilogram of 3 per cent U-235, 5.5 kilograms of natural uranium feed (i.e., 0.711 per cent U-235) must be supplied to the enrichment plant and 4.3 SWUs are utilised. The process also results in the production of 4.5 kilograms of 0.2 per cent depleted U-235 (or tails). Schematically this process can be illustrated as follows:




By increasing the number of SWUs, it is possible to obtain the same amount of enriched uranium with a smaller quantity of natural uranium (and *vice versa*). As a consequence, there would be a corresponding decrease (increase) in the tails assay since a greater (lesser) degree of 'separation' must take place and hence the depleted uranium will contain a reduced (increased) percentage of U-235. Thus 6.6 kg of natural uranium feed combined with 3.4 SWUs would also have produced 1 kg of enriched uranium, but this time with 5.6 kg of depleted uranium with a 0.30 per cent tails assay. Some examples of the effect of varying tails assay on the demand for natural uranium and SWUs are given in Table 1.

As the relative price of natural uranium to SWUs changes, a utility can minimise the cost of its enriched uranium requirements by adjusting its purchases of these two items accordingly. We have already noted that these two items combine to determine the tails assay. The tails assay corresponding to the minimum cost combination of uranium and SWU prices is called the 'optimum' tails assay. Figure 1 illustrates the (nonlinear) relationship between the optimum tails assay and the ratio of the unit cost of feed (natural uranium) to the unit cost of SWUs.

It should be remembered, however, that current technology places a lower constraint of around 0.10 per cent on the tails assay. If laser enrichment were to become a commercial reality this figure could be reduced to around 0.01 per cent. In practice, there appears to be an upper limit of around 0.30 per cent.

**Table 1.** Effect of Varying Tails Assay

| Change in tails assay | | Effect on the demand for natural uranium & SWU arising from reactors using enriched uranium |
|---|---|---|
| From: | To: | |
| 0.20% | 0.16% | − 6% |
| 0.20% | 0.25% | + 9% |
| 0.20% | 0.30% | + 20% |

Source: The Uranium Equation, Uranium Institute, Mining Journal Books, London, April 1981.

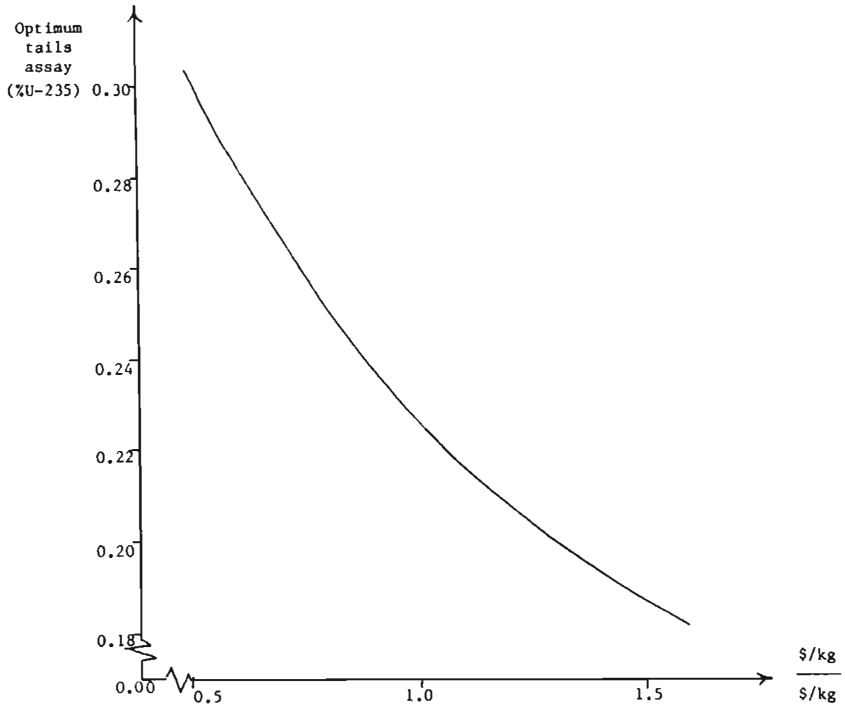



**Figure 1.** Optimum Tails Assay

The optimum tails assay is defined as the ratio of the cost of a kilogram of natural uranium in the form of $UF_6$ to the cost of a kilogram unit of separative work.

For every 0.01 per cent increase in the tails assay, natural uranium consumption increases by about 2 per cent.

Source: NUEXCO, Monthly Report on the Uranium Market, April, 1982.

In the short term a utility's flexibility with regard to achieving the optimum tails assay is limited by its contractual agreement with the enrichment plant which, in general, requires advanced notice of any customer change in tails assay requirements. In the longer term, however, it is apparent from the figures given in Table 1 that changes in the enrichment tails assay can have a very marked effect on the demand for both uranium and enrichment services.

Different enrichment agencies have different pricing schedules, and even within the one enrichment agency prices will vary according to the form of contract negotiated. Since uranium prices also vary according to contract conditions and the dates at which they were negotiated, it follows that there is no unique 'optimum' tails assay. Rather each utility will have its own 'optimum' depending on the price it paid for uranium and SWUs.[1] Since mid-1979 the spot price of uranium has been falling whilst the cost of separative work undertaken by enrichment plants has been rising fairly rapidly. Consequently, the optimum tails assay has increased from around 0.20 per cent U-235 in mid-1979 to 0.30 per cent by mid-1982.[2]

## THE DEVELOPMENT OF AN ENRICHMENT INDUSTRY

In the aftermath of the Second World War, the USA and USSR constructed gaseous diffusion enrichment plants to satisfy their demand for highly enriched uranium for military purposes.[3] Whilst the Oak Ridge (Tennessee) enrichment plant was constructed during the war (1943), US enrichment capacity was considerably expanded by the construction of additional plants at Paducah (Kentucky) and Portsmouth (Ohio) in 1955. All three plants are government-owned but operated by private companies.

Until the mid-1970s, the US Government, through the Atomic Energy Commission (AEC), the Energy Research and Development Administration (ERDA) and, more recently, the Department of Energy (DOE), had a monopoly on the provision of enrichment services in the World Outside the Centrally planned economies Area (WOCA). This allowed it to encourage the expansion of nuclear power by providing utilities with all of their enriched uranium requirements at a very favourable price. Thus, any uncertainty attached to the availability of fuel was removed under the so-called 'Requirement' contracts which were in existence at this time.

Commencing in 1968, US utilities were permitted to purchase $U_3O_8$ direct from the mines and contract for its conversion and enrichment. In order to encourage utilities to enter into long term contracts for enrichment services (and hence uranium supplies), in 1973 the AEC introduced the Long Term Fixed-Commitment Contract (LTFC). By 1974 the AEC, having sold all forward production from its existing and committed enrichment facilities, closed its books and this created a market for new suppliers of enrichment services.

Whether the LTFC was devised to ensure the long-term security of energy supply, or as a shot in the arm for the ailing US uranium mining industry, or as a gesture of encouragement to private (or non-US) enterprise to enter the enrichment market is uncertain. It certainly initiated all three possibilities, although a somewhat less heavy-handed approach may, in retrospect, have been more conducive to the long-term stability of the uranium mining industry.

During the years that ERDA enjoyed a monopoly on the provision of enrichment services, US utilities were not free to select the tails assay they may have required. For many years ERDA pursued a 'split-tails' policy in order to run-down the large (50,000 tons $U_3O_8$) US Government stockpile. Thus the contractual tails assay of 0.20 per cent (for which the utilities would deliver the necessary uranium feed and pay for the corresponding number of SWUs) was generally lower than the operating tails assay (i.e., that actually used by ERDA). The extra uranium that was required to operate this scheme came from the stockpile. As a consequence, utilities were paying for more SWUs than were actually used.

The sharp fall in orders for nuclear power reactors in the late 1970s, together with widespread cancellations and deferments of existing orders (especially in the USA), meant that US enrichment plants no longer had full order books. The entry of two consortiums of Western European nations (Eurodif and Urenco) into the market at this time, together with the willingness of the USSR to supply enrichment services to Western Europe, forced ERDA (now the Department of Energy) to alter its terms in the face of more flexible terms offered by these new competitors. The current status of the four major contributors to WOCA's enrichment capacity is given in Table 2.

European enrichment plants have adopted a commercial pricing policy. The DOE has a cost-recovery selling price policy. But cost (as defined by the DOE) does not include any significant taxes or appreciable capital amortisation. Consequently, US enrichment services are cheaper than the European product. Depending on the type of contract, at November 1981 the DOE price for enrichment was in the range of \$130.75–\$141.15/SWU, whereas Eurodif and Urenco services were sold at \$170–\$180/SWU. The recent rise in the US dollar, however, has almost eroded this gap.

Eurodif, a joint venture between France (the major partner), Belgium, Italy and Spain (Iran was originally a member), has a gaseous diffusion plant at Tricastan in France. This plant attained full capacity in 1982 with member nations committed to taking delivery of enriched uranium in proportion to their shares in the project. Current capacity, however, is sufficient to supply all of Western European requirements during the mid-1980s. More recently, Urenco, a joint UK, Dutch and West German venture, commenced uranium enrichment on a relatively small scale using centrifuge technology. Since centrifuge technology allows the gradual expansion of enrichment plants, future expansion plans will depend upon market conditions.

Expansion of US enrichment capacity at Portsmouth is planned for the late 1980s. The first two increments of 1.1 SWU capacity of an add-on gaseous centrifuge plant are scheduled for completion in 1988 and 1989. Additional increments of 1.1 million SWU/year up to the nominal full capacity of 8.8 million SWU/year will be added as required by the enrichment market. A second European gaseous centrifuge enrichment agency (Coredif) is planned by the Eurodif consortium. The proposed ultimate capacity is 10 million SWU/year.

**Table 2.** Current (1982) Enrichment Capacity Available to the Western World and Tails Assay Flexibility

| Agency | Location | Capacity (million SWU/year) | Variable Tails Range | Notice of Alteration | Estimated or Reference Tails |
|---|---|---|---|---|---|
| US DOE[1] | USA | 27.3 | 0.16–0.30% | 15 months prior to delivery | 0.20% |
| EURODIF | France | 10.8 | 0.18–0.32% | 4 years prior to year of delivery | 0.25% |
| URENCO | Holland<br>UK | 0.6<br>0.4 | 0.20–0.30% | 4 years prior to initial delivery | As set by customer |
| TECHS-NAB-EXPORT | USSR | 2–4[2] | 0.20% upwards | 9 months prior to year of delivery | 0.20% |
| TOTAL CAPACITY | | 41.1–43.1 | | | |

[1] These figures relate to the US Department of Energy's Adjustable Fixed-Commitment contract. The Requirements and Long-term Fixed-Commitment contracts do not allow for a variable tails assay nor for notice of alteration. The draft of a new enrichment contract which has been designed to improve the competitive position of the US Department of Energy has recently been released. It is due to be brought into practice on July 1, 1983.

[2] The figure given for Techsnabexport represents contracts with Western European utilities until 1990, not capacity.

Source: Adapted from The Uranium Equation, Uranium Institute, Mining Journal Books, London, 1981.

## DETERMINANTS OF ENRICHMENT REQUIREMENTS

The fuel requirements of the current generation of Light Water Reactors (LWRs), assuming a two-thirds Pressurized Water Reactor (PWR) and one-third Boiling Water Reactor (BWR) mix, necessitate an average separative work requirement of a little over 100,000 SWU/GWe per annum (assuming a 70 per cent capacity factor and a 0.20 per cent tails assay). Given projections of installed nuclear capacity to the year 2000, it is therefore possible to forecast the corresponding level of separative work requirements for a range of alternative assumptions regarding:

(i) reactor mix;
(ii) recycling and reprocessing;
(iii) tails assay;
(iv) stockpile policy;
(v) political factors.

These five factors will now be considered individually.

### *Reactor Mix*

OECD projections of installed nuclear capacity to the year 2025 indicate that LWRs, and in particular the PWR, will increase their already substantial share (currently about 87 per cent) of the WOCA market using a once-through fuel cycle (i.e., no recycling of spent fuel).[4] Improved technology with the PWR programme could lead to a reduction in both uranium and SWU requirements per GWe, but the effect on the latter is unlikely to be very noticeable before the end of this century.

Over the same period, the significance of reactors which do not make demands on enrichment capacity is projected to remain very minor, with only the Pressurized Heavy Water Reactor (PHWR), the Fast Breeder Reactor (FBR), and the Gas-cooled reactor (GCR) being operational. Only Canada will have a significant capacity in PHWRs, whilst the GCR will gradually be superseded by the Advanced Gas Cooled Reactor (AGCR) which requires its fuel to be enriched. By the year 2000, only France is projected to have a significant FBR capacity operational. Widespread adoption of the FBR, however, would eventually reduce the demand for SWUs, but this appears an unlikely event until well past the turn of this century.

### *Recycling and reprocessing*

Spent fuel can be reprocessed to separate the residual uranium (U-233) and reactor produced plutonium from the waste products generated as a result of fission in the reactor. The recovered uranium re-enters the fuel cycle at the conversion stage and thus its recovery directly influences the demand for uranium. The recovered plutonium, however, re-enters at the fuel fabrication stage either to produce fuel for FBRs or, in the future, for use in plutonium-burning or mixed oxide LWRs. Whilst plutonium recovery directly influences the demand for both uranium and enrichment services, it is unlikely to be a factor of any consequence until well past the year 2000.

### *Tails assay*

We have already noted the considerable impact that can be made on the demand for both uranium and enrichment services by varying the enrichment tails assay. The OECD assumption of a 0.20 per cent tails assay is, at present, substantially below the optimum tails assay (based on the cost of US enrichment services and the US spot price for uranium). This situation, induced by a world-wide glut of uranium, is likely to continue through at least the 1980s. Currently, the optimum tails assay is slightly higher than the maximum limit (0.30 per cent) that is permitted by most enrichment agencies.

### *Stockpiling policy*

Whilst different utilities and different nations will have varying strategies regarding the optimum level of stockpiles, stocks amounting to approximately 2 years of forward requirements are generally regarded as ideal. Currently WOCA stocks amount to approximately 5½years of WOCA forward consumption (and are continuing to rise), which is excessively high by any yardstick.

### *Political factors*

US non-proliferation policy has, in the past, attempted to prevent the spread of enrichment technology to areas/countries which are politically 'sensitive'. Thus the supply of enrichment services was driven more by political and strategic factors rather than economic ones. Recently, however, Brazil has acquired enrichment technology from West Germany, whilst South Africa has developed her own enrichment process.

## *PROJECTIONS OF ENRICHMENT REQUIREMENTS*

On the basis of the most likely combination of the above factors, the OECD has produced projections of future levels of enrichment requirements based upon projections of the rate of growth of nuclear power in WOCA nations. The OECD's projections of nuclear power growth to the year 2025 for the four major regions of WOCA are summarized in Table 3. Whilst the maximum estimates for the years to 1990 are relatively fixed due to the long lead-times involved in the planning, construction and licensing of nuclear power reactors, the lower bound may be subject to significant variation as projects are expanded or contracted. Currently it appears that even the 'low' estimates for 1985 and 1990 are over-optimistic.

Beyond 1990 the degree of uncertainty associated with the projections in Table 3 is reflected in the substantial difference between the low and high estimates. Such a degree of uncertainty is warranted given the dramatic revisions that have occurred in projections of nuclear power growth made over the past decade. This point is illustrated by Table 4, which shows the plunge that took place during the 1970s in the anticipated rate of growth of nuclear power. This variability must be borne in mind when considering the current projections.

**Table 3.** Projections of WOCA Nuclear Power Growth (GWe) (installed nuclear capacity, year-end)

| | 1980 | 1985 | 1990 | 1995 | 2000 | 2025 |
|---|---|---|---|---|---|---|
| OECD Europe | 47 | 94–95 | 142–158 | 171–219 | 223–317 | 457–911 |
| OECD America | 58–60 | 96–119 | 138–156 | 157–185 | 185–235 | 289–643 |
| OECD Pacific | 15 | 28–30 | 51–53 | 67–84 | 89–131 | 169–360 |
| Developing WOCA | 3 | 14 | 30–33 | 56–72 | 88–121 | 396–880 |
| WOCA | 124–126 | 232–258 | 361–399 | 451–560 | 585–804 | 1311–2794 |

Source: Adapted from Nuclear Energy and Its Fuel Cycle: Prospects to 2025, OECD, Paris, 1982.

Table 5 provides estimates of separative work requirements corresponding to the nuclear capacity projections given in Table 3. The data for OECD America refers exclusively to the USA, since the current generation of Canadian PHWRs do not require their fuel to be enriched. The OECD nations in Europe who will require substantial amounts of separative work during the remainder of this century are Belgium, the Federal Republic of Germany (FRG), France, Italy, Spain, Sweden, Switzerland, and the United Kingdom (UK). France will dominate this group, however, and should account for about 50 per cent of Western European requirements.

OECD Pacific data refers exclusively to Japan, whilst the Developing WOCA data is dominated by South East Asia. Overall, SWU requirements by the year 2000 are projected to be at least 350 per cent higher than 1980 requirements, with the major (potential) growth occurring in the decade of the 1990s.

**Table 4.** Past Projections of WOCA Nuclear Power Growth (GWe) (installed nuclear capacity, year-end)

| | Projections for 1980 | | | | Projections for 1990 | | | |
|---|---|---|---|---|---|---|---|---|
| Year of data | OECD Europe | OECD America | OECD Pacific | WOCA | OECD Europe | OECD America | OECD Pacific | WOCA |
| 1968 | 88–118 | 124–128 | 16–18 | – | – | – | – | – |
| 1970 | 99 | 158 | 24 | 300 | – | – | – | – |
| 1972 | 87 | 138 | 33 | 264 | 373 | 539 | 106 | 1068 |
| 1975 | 65–79 | 89 | 17 | 179–194 | 264–380 | 426 | 85 | 875–1004 |
| 1977 | 60 | 66 | 15 | 146 | 195–273 | 214–287 | 50–80 | 504–700 |
| 1979 | 54–61 | 68–72 | 17 | 144–159 | 166–209 | 177–214 | 45–60 | 434–534 |
| 1980 | 47 | 58–60 | 15 | 124–126 | 142–157 | 138–156 | 51–53 | 361–399 |

Source: As for Table 3.

**Table 5.** Projections of Annual Separative Work Requirements (million SWU/annum) (0.20 per cent tails assay, 70 per cent capacity factor)

| | 1980 | 1985 | 1990 | 1995 | 2000 |
|---|---|---|---|---|---|
| OECD Europe | 8 | 11–13 | 14–16 | 19–25 | 24–36 |
| OECD America | 7 | 11–12 | 15–16 | 15–18 | 18–24 |
| OECD Pacific | 2 | 4–4 | 6–7 | 8–11 | 10–16 |
| Developing WOCA | 1 | 2–2 | 4–5 | 7–9 | 11–16 |
| WOCA | 18 | 28–31 | 39–44 | 49–63 | 63–92 |

Source: As for Table 3.

## *PROJECTIONS OF ENRICHMENT CAPACITY*

Projections of uranium enrichment capacity to the year 1995 are given in Table 6. This Table does not take account of the small enrichment plants currently under construction in Brazil and South Africa, nor does it consider the possible/planned entry into the enrichment market of Australia and Canada.

By comparing Tables 5 and 6, it can be seen that current enrichment capacity is far in excess of current requirements and is likely to remain so until the turn of the century if all expansion plans come to fruition. If Urenco continues with its planned expansion, then by 1990 all major Western European uranium consuming nations (with the exceptions of Sweden and Switzerland) will be self-sufficient in enrichment requirements.

Current US enrichment capacity greatly exceeds its domestic requirements, and this situation is envisaged to continue throughout the 1980s. Clearly the demand for enrichment services from nations of the developing world is an important consideration in US expansion plans, but the Western European enrichment agencies will also be in a position to meet this demand.

**Table 6.** Projections of Uranium Enrichment Capacity (year-end) (million SWU/year)

| | 1980 | 1985 | 1990 | 1995 |
|---|---|---|---|---|
| France[1] | 6.0 | 10.8 | 11.8 | 14.8-16.8 |
| FRG[2] | - | 0.4 | 1.0 | - |
| Holland[2] | 0.2 | 1.1 | 3.6 | 6.0-6.9 |
| UK[2] | 0.5 | 0.8 | 3.3 | 5.5-6.6 |
| USA | 26.4 | 27.3 | 30.6 | 36.1 |
| Japan | 0.02 | 0.35 | 2.5 | 5.5 |
| Total | 33.12 | 40.75 | 52.8 | 74.9-78.4 |

[1] Eurodif plant at Tricastan (France)
[2] Joint partners in Urenco

Source: As for Table 3.

Whilst Japan has plans to expand its domestic enrichment industry beyond the gaseous centrifuge demonstration plant at Ningyo-Toge, it will remain a net importer of enrichment services over the remainder of this century.

## *ASSESSMENT OF THE ENRICHMENT MARKET*

The current level of WOCA uranium enrichment capacity is sufficient to satisfy the enrichment requirements (based upon OECD projections of installed nuclear capacity) of the WOCA nations until at least the mid-1990s. If expansion plans for the 1980s come to fruition, these will only serve to exacerbate this surplus supply situation.

OECD projections of separative work requirements are based upon projections of installed nuclear capacity combined with assumptions regarding reactor mix, recycling and reprocessing policies, the level of the enrichment tails assay, stockpiling policy, and political factors. Of critical importance are basic assumptions concerning the optimal level of the enrichment tails assay and the capacity factor for installed capacity. It is now apparent that not only are the recent OECD projections of installed nuclear capacity to the year 2000 over-optimistic, but that the level of separative work requirements has also been over-estimated because of errors in these two basic assumptions.

The OECD's 'low' projections for installed nuclear capacity given in Table 4 now represent over-optimistic forecasts for several major uranium consuming nations. In particular, it is extremely unlikely that (given current lead times) US installed nuclear capacity will exceed 150 GWe by the year 2000. Similarly, Japan is unlikely to exceed a level of 75 GWe. The expansion plans of both nations have been curtailed as a result of the current industrial recession and, in the USA in particular, adverse publicity surrounding the safety of nuclear power which is reflected in lengthening delays in obtaining operating licenses. A total of 41 reactors, representing a combined capacity of approximately 46 (net) GWe, has been cancelled in the USA over the period 1979–1982, whilst no new orders have been placed over this period. Recently, the prospects for nuclear power in the USA received a further setback with the publication of a DOE study which estimated that coal-fired plants scheduled for operation in 1995 would, in general, produce cheaper electricity than their nuclear counterparts.[5] WOCA installed nuclear capacity by the year 2000, therefore, is likely to be substantially below the projections given in Table 4, with a corresponding reduction in enrichment requirements.

The current world-wide surplus of uranium has forced the spot price down to its lowest level (in real terms) since spot prices were first recorded in 1968. Since the cost of separative work has been rising over the past few years, the optimal tails assay has been pushed up to just over 0.3 per cent. OECD forecasts of enrichment requirements, however, assume a 0.2 per cent tails assay. If the average tails assay requested at the enrichment stage rises to 0.3 per cent, this would represent a decrease of 20 per cent in SWU requirements over those projected by the OECD. Thus the current level of uranium prices is encouraging a conservation of enrichment capacity and this situation appears unlikely to change during the 1980s.

OECD projections of enrichment requirements also assume a 70 per cent capacity factor which, on the basis of past experience, is too high. During the year ended June 1982, the capacity factor (weighted by reactor size) of WOCA countries was 60 per cent for both PWRs and BWRs and this figure was reasonably representative for overall LWR performance over the past decade. Only the PHWR has consistently maintained a capacity factor in excess of 70 per cent, but this type of reactor accounted for only 4.4

per cent of total WOCA installed nuclear generating capacity in mid-1982 and does not require its uranium to be enriched. The impact of this lower than anticipated capacity factor is to lower the demand for enriched uranium, and hence enrichment services, by approximately 14 per cent.

A 60 per cent capacity factor combined with a 0.30 per cent tails assay would result in a fall of approximately 31 per cent in enrichment requirements below the projected levels given in Table 5. When reductions in the level of projected installed nuclear capacity are also taken into consideration, it is apparent that OECD projections of the demand for enrichment services represent a substantial over-estimate. It appears likely, therefore, that the current level of enrichment capacity (given in Table 2) will be sufficient to satisfy annual demand until the end of the century. Any expansion by existing or new suppliers of enrichment services over the next decade, therefore, is likely to be largely at the expense of US plants, some of which are nearing the end of their economic life.

## *PROSPECTS FOR AN AUSTRALIAN ENRICHMENT INDUSTRY*

The world uranium market is currently in a state of depression. WOCA uranium production is approximately double current consumption with the surplus passing into a largely unintended accumulation of inventories. The fairly rapid expansion of uranium requirements that is envisaged to occur during the 1980s should ensure that this surplus diminishes over the decade, but excessive levels of inventories are certain to maintain a dampening influence on the uranium market unless a major stimulation of demand can be achieved.

Australia and Canada combined account for almost half of the world's known reserves of uranium. Whilst Canada has been an established producer continuously since the late-1940s, the Australian uranium industry is still at the fledgling stage of development. Production figures for 1981 and projections for the years to 1990 are given in Table 7. It can be seen that the USA's once-dominant role as a uranium producer is expected to decline rapidly over the decade with Canada experiencing the only major growth. Overall production is expected to stagnate throughout the 1980s.

Over the same period WOCA uranium consumption is projected to increase by 70 per cent (Table 8), with the bulk of this expansion taking place in France, Japan and the USA. This relatively rapid rate of growth reflects the coming on-stream of additional nuclear capacity in France and Japan which was ordered during their expansionary phases in the late 1970s. In the case of the USA, longer lead times mean that many plants ordered in the early 1970s will be entering service during the 1980s.

If Australia attains the role of a major uranium exporter, her financial returns can be maximized by ensuring that all uranium exported must be in the most highly processed form possible. Since enrichment plants require considerable supplies of energy, Australia's abundant and cheap coal supplies could be used to provide power[6]. An enrichment plant, however, is a highly capital intensive and very expensive project. It is essential, therefore, to ensure that the return on the invested capital will exceed that for projects competing for the same funds (e.g., the North-West Shelf natural gas project).

**Table 7.** World Uranium Production Forecast (thousand tons $U_3O_8$)

| Producer | 1982 | 1983 | 1984 | 1985 | 1990 |
|---|---|---|---|---|---|
| Australia | 5.6 | 5.2 | 5.2 | 4.1 | 7.0 |
| Canada | 9.5 | 10.7 | 11.7 | 11.6 | 15.4 |
| Central Africa | 6.7 | 6.7 | 6.7 | 6.7 | 6.7 |
| France | 3.4 | 3.6 | 3.8 | 3.8 | 3.8 |
| Namibia | 5.3 | 5.0 | 5.0 | 5.0 | 5.0 |
| South Africa | 8.3 | 8.8 | 9.2 | 9.2 | 8.9 |
| U.S.A. | 14.0 | 10.6 | 9.5 | 8.8 | 7.5 |
| Other | 1.3 | 2.0 | 2.0 | 2.0 | 1.8 |
| Total WOCA[1] | 53.8 | 52.5 | 53.0 | 51.1 | 56.0 |

[1] Individual figures do not sum to the total due to rounding.

Source: NUEXCO, Monthly Report on the Uranium Market, April 1982.

**Table 8.** Apparent Future Consumption (thousand tons $U_3O_8$)

| Buyer Group | 1982 | 1983 | 1984 | 1985 | 1990 |
|---|---|---|---|---|---|
| U.S.A. | 10.7 | 14.1 | 14.3 | 15.7 | 18.9 |
| Europe | 12.3 | 18.1 | 16.6 | 17.3 | 20.1 |
| Far East | 3.4 | 2.8 | 4.9 | 4.9 | 5.3 |
| Other | 2.0 | 2.7 | 2.7 | 2.7 | 4.1 |
| Total WOCA[1] | 28.3 | 37.6 | 38.3 | 40.6 | 48.2 |

[1] Individual figures do not sum to the total due to rounding.

Source: As for Table 7.

At present, all Australian uranium exports leave the country in the form of $U_3O_8$. It is certainly feasible to require that all

Australian uranium be upgraded to $UF_6$ prior to export, and Canada maintains such a policy. But, apart from Japan, all major consumers of enriched uranium have substantial commercial interests in enrichment plants and any attempt at tying uranium supply to enrichment services may lead customers to purchase their $U_3O_8$ elsewhere. It would appear prudent, therefore, to encourage the participation of some major consumer nations in any Australian enrichment project. Any association with an existing uranium enrichment enterprise would also bring the benefits of technical knowledge and experience.

The cost of constructing a centrifuge enrichment plant is approximately \$500 per SWU of annual capacity. Thus for a plant with a capacity of 1 million SWU a year, the construction cost would be about \$500 million. This would provide sufficient fuel for about ten 1 GWe Light Water Reactors[7], which is roughly equivalent to half of Japan's enrichment requirements in 1982. Since centrifuge plants can be built-up in stages as warranted by demand, such a plant could eventually be extended to an annual capacity of (say) 5 million SWU over a period of years. This would involve a total cost of about \$2,500 million (1982 dollars), plus the cost of providing power and debt servicing. This is marginally below the estimated cost of developing the North-West Shelf natural gas project.

By 1990 Australia's uranium production is projected to reach 7,000 tons $U_3O_8$. If all of this output were sold it would represent the annual fuel requirements for about 38 GWe of (Light Water) nuclear generating capacity.[8] This figure would supply the fuel requirements for a 4 million SWU enrichment plant if all exports of uranium were required to be in enriched form before leaving Australia.

Four Australian companies (B.H.P., C.S.R., Peko-Wallsend and Western Mining) have formed the Uranium Enrichment Group of Australia (UEGA) to investigate the feasibility of a commercial uranium industry in Australia. A 'pre-feasibility' study was completed in June 1981 and a full feasibility study is now under way. A separate study by The South Australian Uranium Enrichment Committee is being conducted on the suitability of siting the enrichment plant in South Australia. The Northern Territory, Queensland and Western Australia have also expressed interest in providing a site for the proposed plant.

Whilst UEGA has considered proposals from both France and the Urenco consortium regarding a joint-venture, it is apparent that the recently elected Federal Labor Government is unlikely to condone any commercial relationships with the French regarding uranium enrichment. Thus the Urenco consortium and Japan would appear to be the most likely partners for this venture. The latter would provide a sizeable market for the plant's output, whilst the former would provide technical experience (together with a small market bearing in mind their domestic enrichment capacity). Whether a centrifuge enrichment industry could operate at a commercial rate of return on such a large investment is an unknown factor. At present, detailed estimates of potential revenue and costs are not publicly available, if they exist at all. The centrifuge enrichment industry is in its infancy and it is doubtful whether a full enumeration of its commercial viability has been undertaken by Urenco.

The Western European nations who entered the enrichment industry during the late-1970s did so in response to a projected shortfall in enrichment services which was envisaged (in retrospect, incorrectly) to occur in the mid-1980s. The cost of failing to obtain sufficient supplies of enriched uranium to fuel their rapidly expanding nuclear power programmes would have been politically and economically unacceptable. Security of supply for member countries, therefore, was probably of much greater importance than commercial viability when the Eurodif and Urenco consortiums were formed. Australia, with no domestic market for enrichment services, cannot afford such a luxury!

## NOTES AND REFERENCES

1. The price of uranium is conventionally expressed in US dollars per pound of uranium oxide ($/lb $U_3O_8$), or per kilogram of uranium oxide ($/kg.$U_3O_8$), or per kilogram of uranium metal ($/kg.U), where $1/lb $U_3O_8$ = $2.2046/kg. $U_3O_8$ = $2.6128/kg.U.
2. Strictly speaking, there is no spot market for uranium. NUEXCO, the world's principal private uranium broker, issues a monthly 'Exchange Value' which represents their judgement of the price at which transactions for significant quantities of uranium could be concluded on the last day of the month. Whilst NUEXCO emphasises that their exchange value is not a 'spot' price in the usual sense of the word, nevertheless it is generally regarded as an indicator of uranium spot market price levels. About 10 per cent of uranium requirements in the USA are traded on spot or short-term. At the end of December 1982 the spot price was $20.15/lb $U_3O_8$. The average contract price for deliveries in 1982, however, was $38.00/lb $U_3O_8$. Thus the optimum tails assay for the bulk of US consumers would be considerably below that of those obtaining their uranium supplies on the spot market.
3. Four methods of enriching uranium are of current interest: gaseous diffusion, gas centrifuge, aerodynamic processes, laser processes. Gaseous diffusion is the established technology, having been in large-scale operation for nearly 30 years in the USA. The gas centrifuge process, a relatively recent addition to the commercial enrichment market, has two major advantages over gaseous

diffusion: it is more flexible in matching capacity with demand and it is more energy efficient. Both South Africa and West Germany have been developing aerodynamic processes and the latter has sold its technology to Brazil. Laser enrichment is still largely experimental.

4. All references in this paper to data published by the Organization for Economic Co-operation and Development (OECD) refer to Nuclear Energy and its Fuel Cycle: Prospects to 2025, Nuclear Energy Agency, OECD, Paris, 1982.
5. *Projected Costs of Electricity from Nuclear and Coal-fired Plants,* DOE/EIA-035611, Energy Information Administration, US Department of Energy, August 1982.
6. The actual power requirements of any Australian enrichment plant will depend upon the chosen technology. Centrifuge plants need only 5-10 per cent of diffusion plant power requirements.
7. The average annual SWU requirement for current technology LWRs (assuming a 70 per cent capacity factor, a 0.20 per cent tails assay and a 30 year life) is approximately 100,000. Details are from the publication cited in footnote 4.
8. Under the same assumptions made in footnote 7, the average annual fuel requirement for a current technology LWR of 1 GWe capacity is 186 tons $U_3O_8$. Details are from the publication cited in footnote 4.