Western World Uranium Markets 1991-2000

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This article develops a forecast of uranium demand for the world outside the centrally-planned economies (WOCA) for each year during 1991-2000. It also indicates, on the basis of current production profiles and plans for new capacity, the likely level of uranium supply. A supply-demand balance is then calculated and used to draw conclusions regarding likely trends in uranium prices. The study predicts that demand will exceed supply during 1991-95, but that the shortfall can be covered by a small reduction in uranium stocks and is unlikely to result in more than a modest increase in uranium prices from their current low levels. Supply is expected to exceed demand in the second half of the decade, exerting downward pressure on uranium prices and probably returning them to their current levels in real terms. This forecast is based on the assumption that Australia will not develop new uranium mines during the 1990s; if it does so, stocks will rise, exerting strong downward pressure on prices.

Cet article élabore pour la période allant de 1991 à l'an 2000 une prévision annuelle de la demande mondiale d'uranium en dehors des économies planifiées (WOCA). Il indique aussi le niveau probable de l'offre de l'uranium, basé sur les profils de production et sur les projets de capacité nouvelle. Un bilan de l'offre et de la demande est ensuite calculé et sert à tirer des conclusions en ce qui concerne les tendances probables des prix de l'uranium. L'étude prédit que de, 1991 à 1995, la demande dépassera l'offre mais qu'une réduction modeste des stocks d'uranium peuvent combler le montant insuffisant et qu'il est improbable qu'il en résulte une grande augmentation des prix de l'uranium par rapport aux bas niveaux actuels. On s'attend à ce que l'offre dépasse la demande au cours de la deuxième moitié de la décennie, exerçant une pression descendante sur les prix de l'uranium et les ramenant probablement à leurs niveaux actuels en termes réels. Cette prévision est basée sur l'hypothèse que l'Australie ne développera pas de nouvelles mines d'uranium pendant les années 1990; si elle le fait, les stocks augmenteront, exerçant une forte pression descendante sur les prix.

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Introduction

This article provides an estimate of the balance between demand and supply of newly-mined uranium for the world outside the centrally-planned economies (WOCA) over the years 1991-2000 and, on this basis, draws conclusions regarding likely trends in uranium prices during the coming decade. It summarizes the findings of a larger study which involved both a detailed review of WOCA nuclear power programs and an analysis of all existing uranium mines and planned uranium projects in WOCA countries (O'Faircheallaigh, 1990).

Nuclear power plant capacity in WOCA countries is estimated for each year during 1991-2000, and these estimates are then used to calculate uranium demand. As the centrally-planned countries will be self-sufficient in uranium at least until the end of the century (OECD/IAEA, 1987, p.43), it is not necessary to consider their demand for uranium in analyzing future trends in WOCA uranium markets. Uranium supply is estimated by predicting the output of each operating uranium mine and each potential project in WOCA countries, taking into account geological, economic and political factors and, in the case of new projects, having regard to likely delays in 'official' development schedules. It is expected that the Soviet Union and China will export some uranium during the 1990s and an estimate of their exports is included in the supply projections.

The estimates for supply and demand are combined to obtain a supply/demand balance for each year and this is used, in conjunction with an analysis of uranium stocks and of recent trends in uranium markets, to indicate the likely future direction of prices.

The article assumes that there will be no fundamental change in circumstances during 1991-2000 which will radically alter prospects for the nuclear power industry, either negatively (for example, another accident on the scale of Chernobyl) or positively (for instance, a shift towards nuclear power as a result of concern with the greenhouse effect). Events of the first kind are entirely unpredictable, while any shift in public sentiment towards nuclear power will have little effect on uranium demand during 1991-2000, because of the long lead times involved in planning, building and commissioning nuclear power stations.

Predicting Uranium Supply and Demand

It is very difficult to accurately predict future supply and demand for any mineral commodity. Demand depends on the rate and sectoral distribution of economic growth in consuming countries, on changing intensities of use for the mineral across a range of applications and on rates of substitution between different minerals which can perform a single function. Predicting supply usually requires information regarding the investment and production plans of a large number of mineral suppliers and the likely behaviour of firms which recover scrap metal. Where one mineral is produced as a co-product or by-product of another, as frequently occurs, it is also necessary to consider future supply of the other mineral.

In theory, it should be considerably easier to predict supply and demand for uranium than for most other minerals. A very high proportion of demand is accounted for by a single end use, generation of electric power, whereas many other minerals have scores or hundreds of uses. There is no alternative to uranium as a fuel in nuclear power reactors, so the possibility of substitution need not be considered. In addition, planning, construction and commissioning of nuclear power stations requires a considerable period of time (at least six years and up to 15 years), and so planned additions to capacity are usually known well in advance. In combination, these factors should make it easier to predict future uranium requirements accurately, at least in the short to medium term. On the supply side, ownership of mine production and of uranium resources is highly concentrated (Finon, 1989, p.33), which should simplify the task of gauging future patterns of production and investment. And though there are some exceptions, uranium is not generally mined in combination with other minerals.

In fact, the magnitude of errors in predictions of both demand and supply have been greater for uranium than for other minerals[1] and both have been systematically and substantially overestimated. Two factors help to explain this situation.

First, uranium's dependence on a single end use means that unexpected changes in nuclear power programs can have a dramatic impact on demand; commodities with a variety of end uses are much less likely to be affected by unexpected developments in relation to any one of them and indeed errors in forecasting in relation to one end use may cancel out those in relation to another. Unexpected changes in nuclear power programs

1 / See, for example, Radetzki (1981), p.52-53 and Owen (1983). See also the comments by Ian Duncan of Western Mining Corporation at the Uranium Institute's 13th Annual Symposium (*Mining Journal*, 1988, p.262). Philip Crowson has argued that future forecasts of uranium demand have not been more optimistic than those for other metals. However, his comparison is based on Uranium Institute forecasts alone and these, as noted later in the text, have been considerably less optimistic than others. In addition, his data do indicate that demand forecasts for major metals such as copper, lead and zinc were in fact somewhat more realistic than even the Uranium Institute estimates (Crowson, 1986, p.352 and Table 1 (p.353)).

have in fact occurred during recent decades, and especially over the last 15 years.

Second, supply and demand forecasts have usually been carried out by agencies strongly committed to the growth of nuclear power and/or uranium mining (for example, the Organization for Economic Cooperation and Development's Nuclear Energy Agency and the International Atomic Energy Agency (OECD/IAEA), the Uranium Institute, and firms engaged in marketing uranium and nuclear technology such as NUKEM and NUEXCO) and demand forecasts have usually been based on data supplied by governments strongly committed to nuclear power programs. This helps to explain both the fact that forecasts of supply and demand have been systematically over-estimated, and the fact that the tendency to over-estimate demand persisted long after it became apparent that nuclear power programs were running into difficulties in many countries.[2]

In other words, forecasting uranium supply and demand has been as much a political as a technical or economic exercise and this is an important reason for the magnitude of the errors involved. This point is also illustrated by the fact that agencies with strong links to uranium mining (the Uranium Institute; Mining Journal Ltd) have a better track record in forecasting supply and demand than those involved in the nuclear power industry. So, for example, Mining Journal Ltd predicted in 1978 that uranium consumption would be 65,000 t (tonnes) in 1985, as opposed to the OECD/IAEA's 'most probable' estimate of 92,000; actual consumption in 1985 was 40,000 t (O'Faircheallaigh, 1987, p.30). In 1986 the Uranium Institute predicted that consumption would be 49,000 t in 2000; the OECD's 1986 estimate was 62,000 t, but two years later it had already revised this downwards to 52,400 t. This situation may reflect the fact that mining interests have a great deal to lose from over-estimation of uranium demand; indeed, some have already incurred heavy losses as a result of over-optimistic demand projections in the 1970s. Those involved in the nuclear power industry, on the other hand, have much to gain from emphasizing the potential importance of nuclear power. Some may also stand to gain from an over-supply of uranium; power utilities are currently paying the lowest real prices ever for spot market uranium purchases.

Thus poor forecasting of uranium demand and supply is at least partly due to the influence of organizations with a vested interest in future market outcomes and not solely to inherent difficulties in predicting future consumption and production. It should also be noted that the task of estimating uranium demand and supply in the medium term (over a decade) is less complex today than at any time in the last 30 years. Many WOCA countries have completed development of their nuclear power programs for the time being, or will have done so by 1991 or 1992, though France and Japan are notable exceptions. Development of additional reactors may of course be initiated in the near future, but, given the long lead times involved in planning, licensing, building and commissioning nuclear power plants, they will not have an impact on uranium demand before the end of the 1990s. In relation to supply, a substantial proportion of output is accounted for by a small number of producers who are well-established, possess ample reserves and have long-term contracts for a substantial part of their output, while a large part of any additions to capacity over the next decade will come from just a handful of new projects and planned expansions.

This is not to deny the real uncertainties which exist, particularly on the supply side. Assumptions regarding future developments must of course still be made; these are made explicit in relation to each major producer and consumer by providing relevant statistical data on a country-by-country basis.

Uranium Demand, 1991-2000

The first step in predicting uranium demand is to estimate WOCA's nuclear generating capacity for each year during 1991-2000. This is done by

2/ Note, for example, the OECD/IAEA's serious over-estimation of uranium demand as late as 1986 (see text below).

reviewing the nuclear power program of each country individually and, where necessary, making assumptions about when planned additional capacity will come on stream. These assumptions are required because official start-up dates for reactors are frequently unrealistic, ignoring the delays which often accompany nuclear development programs.[3]

WOCA countries with nuclear power programs can be divided into three groups.

Group 1: The first group consists of countries which have well-established programs but have no plans to develop new capacity during the 1990s (though some may do so later); reflecting this, there is general agreement among commentators as to what their nuclear generating capacity will be. These countries include Belgium, Finland, The Netherlands, Sweden (which may close some plants by 2000), Switzerland, Taiwan, West Germany, Yugoslavia, and Canada and the United States (both of which plan to complete their current reactor construction programs in 1992).[4]

The United Kingdom can now also be included in this group. It had planned to construct a number of new reactors during the 1990s, but in November 1989 the Thatcher government announced that, while one reactor under construction would be completed by 1994, plans for three others would be scrapped.[5] Because a number of Britain's older reactors will soon be due for decommissioning, its nuclear generating capacity will decline in the late 1990s.

Group 2: The second (and much smaller) group consists of industrialized and 'newly-industrialized' countries which plan significant increases in their nuclear generating capacity during the 1990s. In **France**, which depends on nuclear stations for 75% of its generating capacity, construction is proceeding on eight reactors with a combined capacity of 10,770 megawatt-electric (MWe) and these are due to come on line during 1990-93. However, the French state generating authority, Electricité de France (EDF), has substantial surplus generating capacity and is significantly under-utilizing its existing power plants. It seems likely that EDF will slow construction on the new plants so as to avoid an even larger surplus. It is consequently assumed that they will come on stream at the rate of one reactor per year over the period 1990-96, rather than during 1990-93.

Considerable uncertainty surrounds the future of **Spain's** nuclear power program. A nuclear moratorium was established under the National Energy Plan for 1983-92, and construction has been halted on four reactors which, if completed, would have a total capacity of 3750 MWe (Valdecabelleros 1 and 2, Lemoniz 1 and 2). It is not yet clear whether this will be continued under the subsequent plan. NUKEM reports that rapid growth in Spain's electricity demand (3.4% per annum since 1983) has increased the likelihood that construction will be resumed on the mothballed Valdecabelleros 1 and 2 reactors (NUKEM, 1989c), but it appears that the two Lemoniz reactors will not be completed for political reasons.

Japan plans to continue expansion of its nuclear program. At the end of 1988, reactors under construction or approved for construction were scheduled to add a further 15,565 MWe of capacity by 1997 and planned reactors a further 11,170 MWe. However, plans for nuclear power development have been delayed and/or downgraded in the past (see, for example *Mining Annual Review*, 1984, p.85) and, though widespread support for nuclear power exists in Japan, local protests have become more common during recent years and licensing of new reactor sites has be-

3/ In Britain, for instance, the Dungeness, Hartlepool and Heysham reactors were delayed for more than 10 years (NUKEM, 1984, p.9).

4/ Long-term plans published by Ontario Hydro in early 1990 do call for the construction of additional reactors, but, given reactor lead-times and the fact that these plans will now be subject to a public hearing process, it is extremely unlikely that any new reactors will be operational by 2000.

5/ This decision resulted partly from the government's failure to persuade British financial institutions that nuclear power plants should be included in the privatization of the country's electricity industry. The institutions took the view that the cost of decommissioning power stations and disposing of nuclear waste were so high as to constitute excessive financial risks (*Guardian*, 1989).

come more difficult, with the result that delays may occur in bringing on some facilities (for further details see Hallam (1988)). Thus, for this forecast, I have modified official schedules for reactor construction, some of which are in any case clearly unrealistic, and have assumed that reactors will commence production a year later than their scheduled start, where they have construction approval, and two years later where they have yet to obtain approval (see O'Faircheallaigh (1990), p.10, for details). These assumptions are certainly not overly-pessimistic, given recent experience in Japan itself and in other countries.

The **Republic of Korea** has awarded contracts for two new reactors with a joint capacity of 1886 MWe, but construction has yet to commence. They are tentatively scheduled to come on stream in 1995 and 1996. A further three reactors are planned, with a joint capacity of about 2800 MWe. Given the lead time involved, it can be assumed that they will not operate before 2000.

Group 3: The final group consists of Third World countries which are developing nuclear power programs; in each case, major uncertainties surround their plans. **India** is currently developing or planning a further 12 nuclear reactors. Two of these are being obtained from the Soviet Union on a turnkey basis, but, as the Soviets will provide the entire fuel supply for these reactors, their capacity need not be considered in estimating WOCA uranium requirements. The remaining 10 reactors would have a combined capacity of 2760 MWe; four of these are under construction, the remainder are in the planning or site development stage. But major doubts exist as to whether these plants will come on line as scheduled and indeed whether some will ever be built. For example, the Kaprapar 1 and 2 reactors, due to come on stream in 1990 and 1991, were only 22% and 17% completed by the end of 1988, and four of the six planned reactors do not yet have completion dates. India has encountered major technical problems in its nuclear power and associated programs (for example, manufacture of heavy water) and it seems certain that development of nuclear power will lag significantly behind plan.

In **Argentina**, two reactors are currently operating, with a joint capacity of 935 MWe. Both have had major technical problems and have operated well below capacity. A third unit (Athuca 2) is under construction and was scheduled for start-up in late 1993, but development has been held up by financial problems. More recently, the government of President Alfonsin has cancelled all construction on reactors planned by the military government.

Only one commercial reactor, Angra 1, is operating in **Brazil**. It encountered major delays before entering commercial production in 1984 and has had serious technical problems, which led to its closure for 16 months ending October 1988. Two other reactors are under construction, but building has been slowed down through lack of funds and the official schedule has been modified accordingly.

Mexico's first commercial reactor came on stream in late 1989, with a capacity of 675 MWe; construction commenced in 1972. A second reactor is about 60% complete and due to start operations in mid-1992, but Mexico's financial problems are reportedly threatening this project. It is assumed here that it will be completed, but not before 1995.

Plans have also been announced to construct single commercial reactors in Pakistan, Egypt and Turkey. However I have not included these reactors in my capacity estimates because considerable uncertainty surrounds their prospects and because even modest delays in their current schedules would put them beyond the time frame of this study. (Their combined capacity would add less than 1% to projected WOCA capacity in 2000.)

Table 1 draws together the figures for individual countries to calculate a forecast of total WOCA nuclear power generating capacity during 1991-2000. It indicates that capacity will grow from 281,948 MWe in 1991 to 310,338 MWe in 2000, an increase of 10.1% or an average annual increase of just over 1.1%.

How does this compare with other forecasts of capacity? Table 2 presents forecasts by the OECD/IAEA (March 1988 and late 1988), NUKEM (April and December 1989), the Ura-

Table 1: Nuclear Power Plant Capacity, WOCA, 1991-2000 (MWe Net)

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Argentina	935	935	935	935	935	935	935	935	935	935
Belgium	5334	5334	5334	5334	5334	5334	5334	5334	5334	5334
Brazil	626	626	626	1700	1700	1700	1700	1700	1700	1700
Canada[1]	13112	13993	14874	14874	14874	14874	14874	14874	14874	14874
Finland[2]	1420	1420	1420	1420	1420	1420	1420	1420	1420	1420
France	56228	57538	58993	60303	61613	63068	63068	63068	63038	63068
W. Germany	21300	21300	21300	21300	21300	21300	21300	21300	21300	21300
India	1578	1798	2018	2238	2238	2238	2458	2678	2678	2678
Italy[3]	-	-	-	-	-	-	-	-	-	-
Japan	30280	31951	33352	35518	37608	38121	39546	42876	42876	43660
Mexico	675	675	675	675	1350	1350	1350	1350	1350	1350
Netherlands	535	535	535	535	535	535	535	535	535	535
Rep. of Korea	7266	7266	7266	7266	8209	9152	9152	9152	9152	9152
South Africa	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800
Spain[4]	7630	7630	7630	7630	7630	9580	9580	9580	9580	9580
Sweden	9640	9640	9640	9640	9040	8290	8290	8290	8290	8290
Switzerland	2886	2886	2886	2886	2886	2886	2886	2886	2886	2886
Taiwan	4884	4884	4884	4884	4884	4884	4884	4884	4884	4884
UK	12100	12100	11902	13002	13002	13002	12480	12480	12180	10846
USA	103055	105382	105382	105382	105382	105382	105382	105382	105382	105382
Yugoslavia	664	664	664	664	664	664	664	664	664	664
Total	281948	288357	291306	297986	302404	306515	307638	311188	310888	310338

Notes:
1/ The published figures on Canada's capacity from 1993 show a slight variation, with some sources citing a slightly higher capacity (15,300 or 15,400 MWe). My figure is derived from NUEXCO (1988).
2/ Finland's total installed capacity is 2300 MWe, but fuel for two of its reactors (capacity 880 MWe) is supplied by the Soviet Union and consequently their capacity should not be considered in estimating WOCA uranium requirements.
3/ Italy had four commercial reactors in operation by 1988 and two others under construction, but in September of that year the Italian government decided to abandon the country's nuclear power program, dismantling three of the operating reactors, mothballing the fourth and converting the two under construction to oil- and gas-fired plants.
4/ Assumes Valdecabellaros on line in 1996.

nium Institute (July 1989) and NUEXCO (July 1988) for 2000 only. All predict that capacity in 1995 and 2000 will be higher than my own estimates; however, the growth indicated by their forecasts is itself far from spectacular (1.8% per annum in the OECD/IAEA's case). The discrepancy in forecasts is larger in the second half of the period, with the figures for 2000 diverging by about 20,000-30,000 MWe, whereas the largest divergence in 1995 is 10,000 MWe.

What explains this discrepancy in forecasts? First and most importantly, the other forecasts assume that the official schedule for new capacity in Japan will be met and, in particular, that reactors which have yet to receive approval for development planning will become operational in the period 1995-2000. Thus both the OECD/IAEA and NUKEM forecasts of Japan's capacity are some 10,000 MWe greater than my own, which accounts for one-third of the total difference. For reasons already explained, it is clear that Japan's official schedule will not in fact be met. To assume that it will gives rise to exactly the sort of over-estimation of future capacity which was so characteristic of the 1970s and 1980s. Such over-estimation can no longer occur in relation to countries where nuclear power programs have reached a plateau; my estimates for the US, the UK, West Germany and Canada, for example, are almost identical to estimates of the OECD, NUEXCO and the Uranium Institute.

Second, the other forecasts assume that the

Table 2: Forecasts of Nuclear Power Plant Capacity, WOCA, 1991-2000 (MWe Net)

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
OECD/IAEA										
Mar 1988	293500	298100	302600	307900	312600	-	-	-	-	341800
End 1988	-	-	-	-	306932	-	-	-	-	332852
NUEXCO										
Jul 1988	-	-	-	-	-	-	-	-	-	340600
NUKEM										
Apr 1989	290900	295200	300600	306300	311300	317000	323700	331200	336600	342900
Dec 1989	288300	292500	297900	302400	307400	310700	317300	324700	330300	336600
URANIUM INSTITUTE										
Jul 1989	288000	295000	302000	307000	313000	314000	319000	324000	331000	337000
AUTHOR										
Jan 1990	281948	288357	291306	297986	302404	306515	307638	311188	310888	310338

Source: OECD/IAEA (1988a; 1988b); NUEXCO (1988a); NUKEM (1989b; 1988c).

nuclear power programs of a number of developing countries (for example, India, Argentina and Brazil) will also proceed according to official schedules. Given the problems these countries have had with their programs to date, this assumption appears to be even less warranted than in the case of Japan.

Third, some of the forecasts do not take into account (because they precede) recent policy announcements which will reduce future capacity. For example, Italy's closure of its reactors is not accounted for; it is assumed that a number of countries (for example, Belgium, Switzerland and Taiwan) will add to capacity in the late 1990s when it now seems that they will not; and no account is taken of the early closure of Swedish reactors. None of the forecasts take account of the recent developments in Britain's nuclear industry.

It should be noted that the later estimates by the OECD/IAEA and NUKEM have moved significantly closer to my own. Between March 1988 and the end of 1988, the OECD/IAEA's forecast for 1995 fell from 312,600 to 306,932 MWe, compared to my figure of 301,904 MWe, while NUKEM's estimate for 1995 fell from 311,300 to 307,400 MWe between April and December 1989. The OECD's figure for 2000 fell from 341,800 to 332,852 MWe, NUKEM's from 342,900 to 336,600 MWe; this compares with my figure of 310,338 MWe. These downward revisions provide substantial support for the validity of the capacity forecast developed in this study.

Three factors have to be considered in calculating the demand for uranium that will be created by the level of nuclear electricity generating capacity indicated in Table 1.[6] The first involves the proportion of installed or nominal capacity

6/ Two factors other than those discussed in the text are also relevant. The first relates to the fact that uranium must be purchased in advance for new reactors, creating a demand for uranium in advance of commissioning dates. This factor is not considered here because the period involved would vary from power utility to power utility and even across reactors, depending, for example, on whether utilities hold fuel stockpiles they regard as surplus (as many currently do) and on their assessment of future market trends. However, the omission of this phenomenon should not significantly affect the demand forecast, given the slow and incremental nature of additions to capacity over the period involved.

The second factor relates to the different quantities of uranium required by reactors at various stages of their life cycles. This factor is incorporated by using a 'standard' ratio of generating capacity to uranium demand that takes account of both newly-commissioned and established reactors (see text).

which is actually utilized during the relevant period, referred to as the 'capacity factor'; the second relates to the operating characteristics of nuclear reactors, which determines how much enriched uranium is needed to support a given 'capacity factor'; and the third involves the level of uranium in the discarded product from uranium enrichment, the 'tails assay.' (The tails assay determines the volume of natural uranium required to produce a given amount of enriched uranium used in reactor fuel. The higher the tails assay, the larger the volume of concentrate required and so the higher the forecast of future uranium demand.)

All three factors are subject to considerable uncertainty, and consequently forecasts of uranium demand can vary widely, even when there is agreement on future nuclear generating capacity. For example, in 1988 both the OECD/IAEA and NUEXCO forecast nuclear generating capacity at 341,000 MWe in 2000, but the OECD translated this into a requirement for 52,400 t U, while NUEXCO translated it into a requirement for 57,845 t U (OECD/IAEA, 1988a, Tables 11 and 12; NUEXCO, 1988a, Tables 1 and 2).

A measure of the overall result of the assumptions made regarding the three factors mentioned above is provided by calculating the uranium said to be required to fuel, on average, one MWe of installed capacity. The higher this figure, the higher the level of uranium demand. In recent years, NUEXCO's figure has been 0.20 for 1988 and 0.17 for 2000, NUKEM's between 0.16 and 0.17 for the 1990s, the OECD/IAEA between 0.15 and 0.156 for the period 1991-2000, and the Uranium Institute's 0.14 for 1995 and 0.13 in 2000 (allowing for reprocessing of spent reactor fuel).[7] I have used the Uranium Institute's figure of 0.14, because the Institute has, in the past, been less prone to over-estimate demand and because its figure is already adjusted to take account of spent fuel reprocessing.[8]

Applying a requirement of 0.14 t U for each MWe of capacity to the last line of Table 1, we arrive at the estimates for reactor uranium requirements indicated in Table 3.

Uranium Supply, 1991-2000

In order to asses likely uranium supply during 1991-2000, information was collected on: (i) all currently-operating WOCA uranium mines which produce more than 100 t U308 (some smaller mines were also included), and (ii) all uranium projects for which public announcements have indicated a possible start to production before 2000 (see O'Faircheallaigh (1990), Appendix 1 and Appendix 2, for details). Information was sought for each mine or project on ownership, mining method, start-up date, nominal capacity and recent production (planned capacity for prospective mines), ore reserves and expected life. These data were used to undertake a country-by-country analysis and this in turn permitted estimation of supply for each year during 1991-2000. (All figures for production, capacity and uranium content of ore reserves are expressed in metric tonnes of uranium oxide, U308). This section provides a summary of relevant findings.

Australia currently has two mines in operation, Ranger and Roxby Downs. Ranger commenced production in 1981, and output has been between 3100 and 3500 t during recent years. The Ranger mine was constructed so as to facilitate expansion at minimum capital cost. In 1986 Energy Resources of Australia (ERA) announced plans to increase production to 4500 t by 1991 and to 6000 t by the end of 1992, but more recently has indicated a more cautious approach, stating its confidence that demand will warrant

7/ The NUEXCO figure is derived from NUEXCO (1988a) Table 1 (p.16) and Table 2 (p.18); the NUKEM figure from NUKEM (1989d), Table 4 (pp.16-17) and Table 5 (p.26); the OECD figure from OECD/IAEA (1988a), Table 11 (p.43) and Table 12 (p.44); and the Uranium Institute figure from the Uranium Institute (1986), Table 2.1 (p.12) and Table 3.1 (p.27).

8/ A more extensive discussion of the assumptions required to convert nuclear generating capacity to uranium demand and a detailed justification for my choice of this figure is provided by O'Faircheallaigh (1990), pp.14, 16-17.

Table 3: Reactor-Related Uranium Requirements, WOCA, 1991-2000 (tonnes U)

1991	39,473
1992	40,370
1993	40,783
1994	41,718
1995	42,337
1996	42,912
1997	43,069
1998	43,566
1999	43,523
2000	43,447

expansion "by the early 1990s." It is consequently assumed that Ranger's output will not be increased until 1992 and that the further expansion to 6000 t will not begin until 1994 and will be spread over 1994-96. On this basis, Ranger's current reserves will support mining well beyond 2000.

Roxby Downs commenced production in 1988. Its initial planned output was 1900 t and the mine was designed to permit a doubling of capacity if market conditions permitted. (Reserves are adequate to support the higher level of production for many decades.) However Roxby has encountered difficulties in marketing part of its planned output and intended to produce only 1450 t in 1989. Negotiations are continuing for further sales contracts. It is assumed that output will increase to 1900 t by 1991, but that further expansion will not occur until 1996 and will be spread over 1996-98.

Australia possesses very large uranium resources and a number of other deposits are fully delineated and could be developed within a short period of time. However, it is assumed here that Australian government policy, which currently prohibits the establishment of new mines, will prevent their exploitation.

Canada is the world's largest uranium producer, with output of 14,700 t in 1988 from five mines or mining complexes. Some 35% of output came from older, low-grade mines at Elliot Lake in Ontario operated by Denison Mines Ltd and Rio Algom, but these are under increasing economic pressure due to high production costs and falling uranium prices. Indeed, Rio Algom has announced that it will close two of its three mines in mid-1991 and projections of its future output have been adjusted accordingly. Denison has long-term contracts with Ontario Hydro and these would be sufficient to absorb its Elliot Lake output until 2012. However, the company is developing a new deposit at Midwest Lake in Saskatchewan, with a planned capacity of 1350 t. It has stated that output from Midwest is aimed at meeting projected growth in uranium demand, but, if growth in demand is lower than Denison expects, it would presumably substitute for higher-cost Elliot Lake output. It is assumed that the combined output of Denison's operations during 1991-2000 will be close to recent output from Elliot Lake; but it should be kept in mind that the company will have the capacity to increase output quickly if demand warrants it.

Cluff Lake is the smallest of the three Saskatchewan producers (1000 t per annum). It is a low-cost producer and its reserves are adequate to support mining for 20 years. It is thus assumed that output will remain at current levels during 1991-2000.

The life of Cameco's Rabbit Lake operations, which increased its output to 3136 t in 1988, has been very substantially extended by the discovery of large reserves in the nearby Eagle Point South and North deposits. Cameco has closed Rabbit Lake for six months from July 1989, partly because of poor market conditions, partly to modify its mill. It has announced that capacity will be increased to 5450 t as a result of the modification. Given the depressed state of the uranium market, it is unlikely that this capacity will be utilized in the short term. However, ore reserves are certainly adequate to support a higher level of output for many years and it appears that output will increase if and when market opportunities become available. It is assumed here that output from Rabbit Lake will increase to 4000 t in 1993 and will remain at that level for the rest of the decade.

Key Lake is the largest uranium mine in the world, with output averaging 5800 during recent years. Its ore reserves are limited, however, and will only support operations until 1998 or 1999. Output is expected to remain at current levels into the late 1990s, but to decline in 1998 and

1999, ceasing at the end of 1999.

Canada also has a number of major uranium projects which are expected to commence production in the 1990s. By far the most important is Cigar Lake, which contains 175,000 t U308 in very high-grade ore and has the potential to be a very low-cost producer. Production is scheduled to commence in 1993 and reach capacity (5500 t) in 1995. This schedule may be optimistic; while test mining is being conducted in 1990, major difficulties are involved in mining very high-grade uranium ores. It is assumed here that production will not commence until 1995 and that full capacity will not be achieved until 1997.

A number of other, smaller deposits are also likely to be developed. Denison's Midwest Lake has already been discussed. Dawn Lake and McClean Lake are scheduled to achieve full production in 1999 but, given their stage of development, little certainty can be attached to this date and it is consequently assumed that they will not produce before 2000. Urangesellschaft is further advanced in its planning for development of Kiggavik in the Northwest Territories, with initial production scheduled for the mid-1990s. Again assuming some delay in development, initial production is assumed to occur in 1998 and full production (1600 t) in 1999.

France has two major uranium mining operations, with both Cogema and the Total group operating a number of small mines and a central milling facility. Each has sufficient reserves to support mining until beyond 2000. Because France depends on nuclear fuel for 75% of its electricity, possession of domestic uranium mining capacity is vital to its energy security. It is therefore inconceivable that uranium mining would cease as long as reserves are adequate to sustain it and it is assumed that France's output will remain at current levels during 1991-2000.

Gabon has one uranium mining venture, located at Mounana; it is operated and largely owned by French interests. During recent years production has averaged 1000 t; its nominal capacity is substantially larger and its output was somewhat higher in the early 1980s, but was reduced in response to poor market conditions. Gabon is a high-cost producer, but its French shareholders purchase much of its output, giving it a secure market. Its ore reserves are more than adequate to support mining for many years and it is assumed that Gabon will produce at recent levels for the rest of the century.

Namibia has one major uranium mine, Rossing, which has produced 4100 t during recent years. There were suggestions that Rossing's output might fall as a result of United Nations trade sanctions against Namibia, but this possibility no longer exists. Indeed its location in newly-independent Namibia may be a positive advantage to Rossing. It is a low-cost producer, its ore reserves are sufficient to support 20 years mining at recent levels and it is assumed that output remains at about 4100 t to the end of the century.

Niger has two major uranium mining operations, at Akouta and Arlit, operated and largely owned by French interests who purchase a substantial proportion of mine output. During recent years their combined production has been about 3700 t. Both have ore reserves sufficient to support mining for about 30 years at this rate and their ownership and market links with French consumers should assure them of continued markets. Niger produced substantially more uranium in the early 1980s (4800 t in 1982), and has the mill capacity and reserves to achieve this level quickly if demand justifies it. However, it is assumed here that output will remain at the current level during 1991-2000.

Uranium is produced in **South Africa** entirely as a byproduct of gold mining and, in one case, of copper mining. Output has fallen steadily during recent years, from about 7000 t in 1980 to an estimated 4500 t in 1988, and was expected to fall below 4000 t in 1989. This reflects poor market conditions for uranium and, since 1988, the impact of trade sanctions. A further decline in output is likely to occur in the near future, assuming that markets remain depressed and that the pressure to enforce sanctions against South Africa continues. It is likely, however, that a number of the major producers will continue to produce at or close to their current levels. In particular, Vaal Reefs and Freegold are two of the largest gold producers in the world; uranium is a byproduct of their gold mining operations and output tends to follow gold production. Their uranium production costs are low and they have adequate ore reserves to support mining well beyond 2000. Despite sanctions they are very unlikely to be denied access to uranium markets, as some consumers are indifferent to the source of uranium, while others have a positive preference for South African material due to the absence of nuclear safeguard provisions. It is assumed that production will fall to 3500 t in 1991, 3000 t in 1994, and 2500 t in 1997 as a number of smaller producers deplete their orebodies. It must be kept in mind, however, that those South African gold mines which have closed uranium facilities can resume production quickly if economic and political circumstances are favourable.

The **United States** has a substantial number of uranium producers. They extract uranium in conventional mining operations, through solution mining, and as a byproduct of phosphoric acid production. Uranium production in the US has fallen sharply during recent years, from nearly 20,000 t in 1980 to about 5500 t in 1987, mainly due to the inability of its low-grade/high cost mines to compete with efficient producers in Australia, Canada and South Africa. It is inconceivable that the US will recover its position as the world's leading producer, but 1988 did represent a turning point for its uranium industry. New projects were established, construction commenced on others and some mines were reopened under different ownership. Production from new or reopened mines amounted to 1975 t in 1988 (O'Faircheallaigh, 1990, Appendix 1) and will be higher in 1989 as new projects achieve full production. These additions to capacity more than offset closures and cut-backs, leading to an increase in output to about 6100 t in 1988.

Many of these new or reactivated projects have low operating costs and are well capable of competing effectively for domestic and export markets. Crow Butte, for example is expected to produce U308 at less than US$10 a pound, while Kingsville Dome had total costs of US$10.57 in 1988 (Uranium Resources Inc, 1988, p.8). It thus seems certain that the US will continue as a major uranium producer, particularly since a number of major foreign mining companies and power utilities have recently purchased both operating mines and undeveloped properties. On the basis of currently-available information, it seems likely that output will be in the region of 7500 t in the early 1990s, rising to 8000 in the mid-1990s, and declining to about 7000 by the end of the decade. This assumes that no new projects or expansions are undertaken which do not currently have published schedules.

The remainder of world production is accounted for by a small number of minor producers (Argentina, Brazil, India, Portugal and Spain). None of these is expected to increase its output dramatically during 1991-2000.

In addition to uranium production from WOCA mines, exports from non-WOCA countries must be taken into account. It is very evident that China, in particular, is keen to become a significant exporter of uranium. It has already made some spot market sales to Europe, concluded long-term contracts with European utilities and in 1988 signed its first long-term contract with a US utility. NUEXCO estimates that China is currently able to export between 900 and 1800 t U308 per annum. The Soviet Union was also active in international markets in 1988, though it is not yet clear whether it will also negotiate long-term contracts. It is assumed here that WOCA imports will average 1500 t/y during 1991-95 and 2000 t/y during 1996-2000. This estimate may prove too low, particularly for the first half of the decade, if economic problems force the Soviet Union, Hungary and Czechoslovakia to export uranium currently held in stockpiles in order to earn foreign exchange.

Table 4 combines these figures with the estimates of production for individual countries to calculate a forecast for WOCA uranium supply in each year during 1991-2000. It indicates that supply from existing and planned mines will grow from just over 45,000 t in 1991 to around 55,300 t in 1997, declining thereafter to around 52,500 in 1999 and 2000.

How does this forecast compare with other estimates of uranium supply? Only NUEXCO attempts to forecast actual production during

Table 4: Primary Uranium Supply, WOCA, 1991-2000 (tonnes U308)

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Australia	5200	6400	6400	6900	7400	8800	9300	9800	9800	9800
Canada	14000	13100	13100	14100	15100	17100	19600	18300	16800	17400
France	3800	3800	3800	3800	3800	3800	3800	3800	3800	3800
Gabon	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Namibia	4100	4100	4100	4100	4100	4100	4100	4100	4100	4100
Niger	3700	3700	3700	3700	3700	3700	3700	3700	3700	3700
South Africa	3500	3500	3500	3000	3000	3000	2500	2500	2500	2500
United States	7500	7500	7500	8000	8000	8000	7000	7000	7000	7000
Argentina	180	180	180	180	180	180	180	180	180	180
Brazil	360	360	360	360	360	360	360	360	360	360
India	140	140	140	140	140	140	140	140	140	140
Portugal	180	180	400	400	400	400	400	400	400	400
Spain	250	250	250	250	250	250	250	250	250	250
Imports	1500	1500	1500	1500	1500	2000	2000	2000	2000	2000
Total	45410	45710	45930	47430	48930	52830	55330	53530	52030	52630
Equivalent tonnes U	38144	38396	38581	39841	41101	44377	46477	44965	43705	44210

1991-2000 and provides a country-by-country breakdown of its forecast. Its figures for the early 1990s are similar to my own, with only between 1000 and 2000 t separating the two estimates. However, there is a significant divergence for the years 1995-99, with NUEXCO's being about 6000 t higher than mine (*Engineering and Mining Journal*, 1989, p.46). The discrepancy is mainly due to NUEXCO's assumption that additional Australian and Canadian capacity will actually come on line as currently scheduled, whereas I have assumed some delays; and that output from what NUEXCO classifies as 'other producers' will rise substantially, from about 5200 t in 1994 to 7400 t in 1997. There is little evidence that any such increase will come from producers such as India, Portugal and Spain; NUEXCO must expect much of it to be accounted for by China. It should also be kept in mind that NUEXCO's forecast of uranium demand is higher than my own.

The Supply/Demand Balance and Uranium Prices, 1991-2000

The demand and supply figures from Tables 3 and 4 are combined in Table 5 to provide a supply/demand balance for newly-mined uranium. This indicates that demand will be in excess of supply during 1991-95, by an average of about 1700 t U per annum. However, during 1996-98 supply exceeds demand by a substantial margin (an average of 2100 t U per annum), mainly due to the coming on line of additional production in Australia and Canada. The excess supply declines at the end of the decade because of the exhaustion of ore reserves at a number of Canadian mines.

What are the implications of these findings for uranium prices? To address this issue, it is necessary to briefly examine the history of uranium markets and prices during recent decades.

Large-scale uranium mining commenced in the 1950s in response to demand from nuclear weapons programs, with the British and US governments offering attractive prices to encourage development of mining capacity (Radetzki, 1981, p.41). By the end of the 1950s, however, military needs had largely been satisfied and commercial demand for reactor fuel had not yet developed. In 1964 the US uranium market was closed to imports. The industry found itself with large excess capacity, prices declined severely and mines were closed in Australia, Canada, the US and South Africa.

Prices rose very rapidly in the mid-1970s, for reasons which have been discussed in detail by Radetzki (1981, pp.116-19) and Finon (1989, pp.39-40). Average spot prices increased by 6.6

Table 5: Uranium Supply and Demand, WOCA, 1991-2000 (tonnes U)

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	**Total**
Supply	38144	38396	38581	39841	41101	44377	46477	44965	43705	44210	419797
Demand	39473	40370	40783	41718	42337	42912	43069	43566	43523	43447	421218
Balance (Supply-Demand)	-1329	-1974	-2202	-1877	-1236	1465	3408	1399	182	763	-1421

times in nominal terms and 4.8 times in real terms between 1973 and 1976 (Radetzki, 1981, p.30). Spot sales accounted for only 5-10% of the total market, but increases in spot prices flowed through to long-term contracts, both by influencing price levels in newly-signed contracts and through renegotiation of existing contracts in favour of producers. However, prices peaked in real terms in 1977 and by 1979 were declining in nominal terms also. This reflected substantial downward revisions of plans for nuclear power development (due to lower growth in energy consumption and to political and economic problems faced by the nuclear industry), changes in the United States government's enrichment policies and, most importantly, the fact that higher prices and the long-term contracts offered by utilities had resulted in development of substantial new mining capacity. Between 1975 and 1980, WOCA uranium production increased at a compound annual rate of over 18% (Townsend, 1983, p.76).

By 1980 production was approximately twice consumption and stock levels had risen very substantially. In early 1985 commercial stocks were estimated by NUEXCO at five years' forward consumption (NUEXCO, 1985, p.13), as opposed to the one or two years' consumption usually regarded as a desirable level. (In comparison, world stocks of copper were only about three months' forward supply.) NUEXCO's average exchange values for spot transactions fell from US$40 in January 1980 to US$17 in August 1982.[9]

Uranium consumption exceeded production for the first time in the history of the civil nuclear industry in 1985. In both 1986 and 1987 production was estimated at about 4000 t less than consumption (*Mining Annual Review*, 1988, pp.83-84). Many commentators expected that this shortfall in supply would lead to a drawdown in stocks which would, in turn, allow some price recovery.[10] However, it must be kept in mind that stocks detailed by member countries to the OECD/IAEA in 1985 totalled 172,000 t U (OECD/IAEA, 1986). Thus the supply shortfall in 1986 and 1987 would have absorbed only 4.7% of total reported stocks, with the balance still equivalent to nearly four years' forward consumption.

In fact prices continued their downward spiral in 1988 and the trend has persisted during 1989 and into 1990. NUEXCO's average exchange value for spot transactions fell from US$16.30 in January 1988 to US$10.70 in March 1989 and fell below US$9.00 in January 1990; the latter is its lowest level ever in real terms. The fundamental cause of the price decline was that utilities continued to draw down stocks and reduce their purchases from uranium producers, leaving the producers to compete aggressively among themselves and with China and the Soviet Union for the remaining orders. The passage of the US-Canada Free Trade Agreement (which improves access for Canadian uranium in the US market), the failure of proposals by US uranium producers for protectionist legislation and the continued downward revision of estimates of future uranium demand have also had an impact.

The continuing decline in prices during 1986-

9/ Spot price quotations are from the historical data presented in NUEXCO (1989), p.24.

10/ A number of examples are cited by Hallam (1988) pp.44-45. See also *Engineering and Mining Journal* (1986).

90 shows very clearly that a modest decline in high levels of uranium stocks is not in itself sufficient to stabilize prices at low levels, let alone bring about price recovery.

Falling spot market prices have already had a major, though lagged, effect on long-term contract prices, and they will continue to do so. According to NUKEM, average contract prices in the US fell from US$34.15 in 1983 to $23.95 in 1987, a decline of 30% in nominal terms (NUKEM, 1989c, p.14). The impact of falling spot prices is even more evident from contracts signed recently between a number of US producers and Japanese utilities for the period 1989-2000; prices are reportedly between US$15 and US$20 per pound of U308 (Hallam, 1988, pp.97-98; *Engineering and Mining Journal*, 1989, p.45). In recent years, long-term contracts based on spot prices have become increasingly popular (NUKEM, 1989a, p.2), which will mean that, in the future, changes in spot prices will flow through to contract prices more directly and quickly. Indeed NUEXCO reports that some producers have been offering **discounts** from spot prices in attempts to secure long-term contracts, and that this in turn has placed further downward pressure on spot prices (NUEXCO, 1988b, p.2).

Against this background, what are the implications of the supply/demand estimates for 1991-2000 contained in Table 5? The first point to note is that stocks will still be very substantial at the start of the period, in excess of 150,000 t U or about 3.5 years' forward consumption.[11] The projected shortfall of supply during 1991-95 can be met by a small reduction in stocks (equivalent to only 5.7% of the total). It thus appears unlikely that prices will increase substantially during 1991-95, though some price recovery is likely. For the remainder of the decade, the figures indicate an over-supply of uranium of about 7200 t, implying an **increase** in stocks of some 5%. This would almost certainly put downward pressure on prices, partly negating any increase achieved during the first half of the decade and returning prices to their current level, which is of course very depressed in historical terms.

This scenario assumes that planned additions to capacity will actually occur in the mid-1990s, particularly at low-cost mines in Australia and Canada (see Table 4). While the modest price increases expected in the early 1990s can be expected to have a positive impact in this regard, it is possible that mining companies will not feel that price levels are sufficient to justify the necessary investments and may delay or cancel planned additions to capacity. In this case prices might continue to recover into the second half of the decade.

On the other hand, the supply estimates in Table 5 assume that delays will occur in the current schedules for all planned expansions and new mines, that spare capacity in Gabon, Niger and South Africa will not be utilized, that Denison Mines will not make a net addition to its total output and that large sales of uranium from Eastern European stockpiles will not occur. They also assume that Australia will not develop any new uranium mines. Development of even one small new uranium project in Australia would more than cancel out the slight supply shortfall forecast for the 1990s, while establishment of a large project would lead to significant over-supply during 1991-95 and result in an even larger build-up of stocks and stronger downward pressure on prices in the second half of the decade.

Conclusion

Taking account of recent developments in relation to existing nuclear power plants and applying realistic (though still possibly optimistic) schedules to new developments, this study has calculated estimates of future nuclear power plant capacity which are slightly lower than other published forecasts for 1995, and significantly lower (by between 7 and 9%) than other forecasts for 2000. These data were then used to calculate demand for newly-mined uranium in each year from 1991-2000.

11/ This figure is based on the Uranium Institute's estimates of reactor requirements for 1988-90 (*Mining Annual Review*, 1988, p.83) and on the assumption that production remains at or near its 1988 level of about 38,000 t U during 1989-90.

The study analyzed detailed data relating to some 40 existing uranium mines and 20 planned projects to estimate supply during the same period. Again, what are regarded as more realistic timetables were applied to the development of additional planned capacity; in particular, some major expansions and new projects currently scheduled to come on line during 1993-96 are expected to commence during 1995-97. Supply is assumed to be significantly below potential capacity, with producers in Canada, Niger, and South Africa in particular expected to under-utilize their production capabilities.

Combining the estimates for supply and demand, the study forecasts a small shortfall in supply during the 1991-95. However, this shortfall can be covered by a slight reduction in the uranium stocks which will exist at that time and, on the basis of experience during recent years, it is unlikely to result in more than a modest increase in prices. Supply is expected to exceed demand significantly from 1996-98 and to exceed demand slightly in 1999-2000. This is likely to exert downward pressure on uranium prices, returning them to their current low levels in real terms.

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