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Reflection on the Uranium Market

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"Get your facts first, and then you can distort them as much as you please" - Mark Twain.

"It's like déjà vu all over again" - Yogi Berra.

Introduction

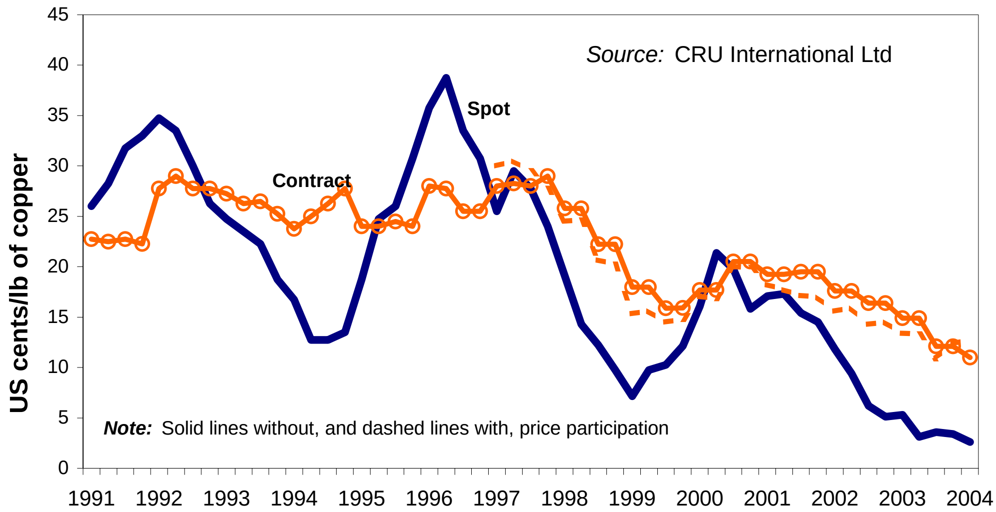
This paper looks back at various aspects of the uranium market over the past thirty years, the lifetime of the World Nuclear Association and its predecessor, the Uranium Institute. It concentrates mainly on how supply has responded to changing circumstances. Unsurprisingly, uranium has shared many of the characteristics of other mining sectors throughout this period. One of the main themes is summed up in the following quotation from the concluding paragraph of an analysis of the uranium industry. "There is no question that uranium prices..… were too low, and that a rise in prices was necessary to provide incentives for exploration and development. Hopefully, the recent upward movement of uranium prices and the liquidation of excess inventories and capacities have provided the stability the industry required to respond to the need for its expansion" <*1*>. Whilst that might have been written within the last two years, it comes from 1975, and refers to the 1960s and early 1970s.

Prices

Trends in prices are a convenient starting point for any reflections on the uranium market. The pricing of uranium has always been relatively opaque, because there is no terminal market quotation and full details of individual contracts are seldom released. The published averages for the United States and European Union embrace a wide range of different pricing arrangements and terms negotiated at different times. Euratom's estimates of annual average spot prices are perhaps the closest to genuine prices, but they are retrospective rather than current. The published averages are, of course, supplemented by quotations and estimates of varying degrees of acceptance and respectability made by various brokers and trade publications. Since their inception, such estimates have always been controversial, roundly condemned by producers when they appear too low and by purchasers when they appear too high. Many of the criticisms are thoroughly misconceived, betraying a wilful ignorance of the basic economics of supply and demand. Prices in a competitive market are determined by what happens at the margin, rather than by the intra-marginal transactions that make up the vast bulk of annual trade. Spot quotations, however they are derived, reflect the prevailing state of trade rather than any historic balance of advantage when a sales contract was first signed. That the various sources give similar levels of spot prices should provide some assurance of their validity. Their similarities are not based on mere plagiarism.

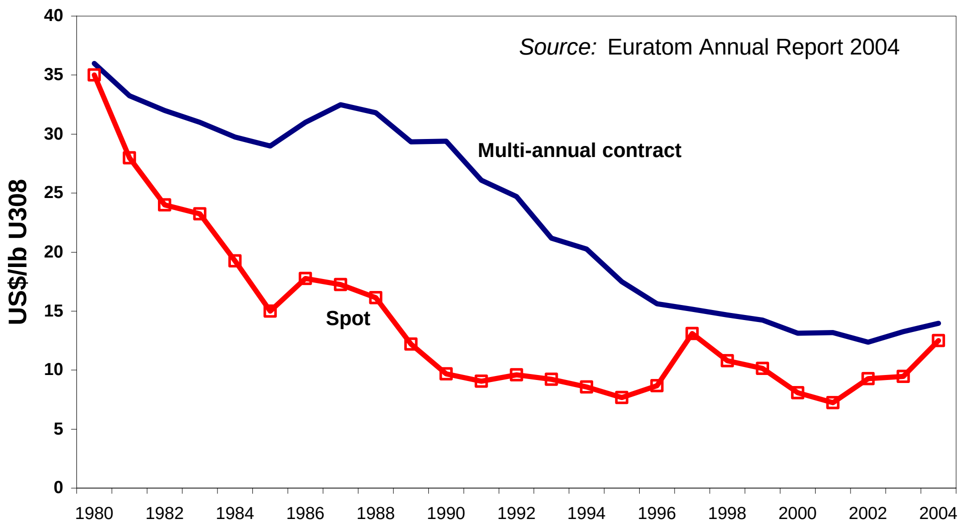
As the example of the copper concentrate market demonstrates, spot prices are invariably more volatile than contract prices, and the latter tend to lag behind changing market conditions. Copper concentrate is similar in many respects to uranium in that it has only one use and requires further processing. The charges are the amounts deducted from the price of copper metal by smelters, who normally buy concentrates outright. Over time the length of the lags has diminished as the pricing clauses of concentrate contracts have become more and more driven by prevailing market conditions. Fixed price and formula based pricing have greatly diminished in importance. That is true of many other mineral products, including uranium.

Figure 1. Treatment and refining charges for 28-30% copper concentrates, 1991-2004



In contrast to copper concentrates, whose spot prices fluctuated around contract prices, spot prices of uranium have generally been below contract prices for over twenty five years. In that regard *Figure 2* compares the annual averages published by Euratom for multi-annual contract and spot prices.

Figure 2. Euratom annual average uranium prices, 1980-2004

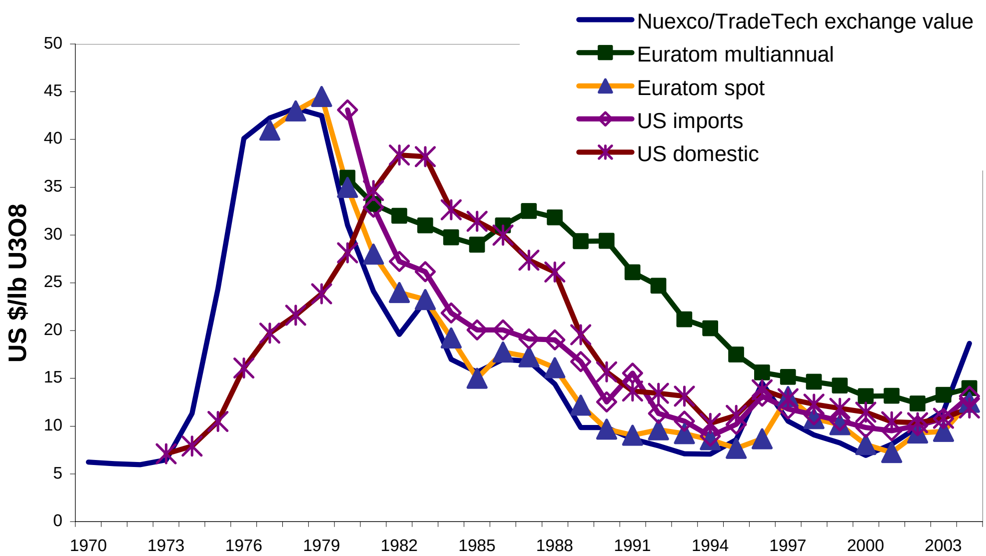


The continuing gap between contract and spot prices reflects persistent oversupply over the period rather than an inevitable tendency. The gap was at its narrowest in 1980, shrank temporarily in 1997 and contracted again in 2004. Spot prices will probably rise above contract prices in the next few years.

Euratom's measures of price are compared with other measures in *Figure 3* <2>.

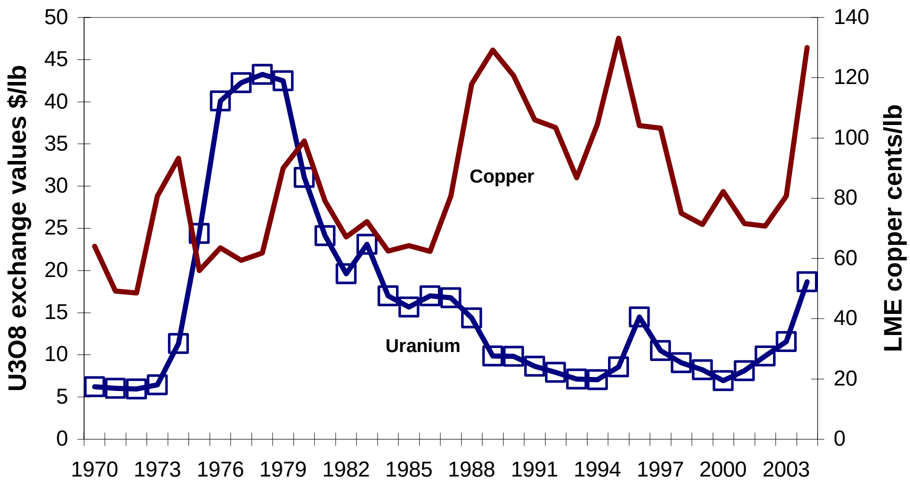
The Nuexco/TradeTech exchange value is here used as an indicator of spot prices solely because of its longevity.

Figure 3. Measures of uranium prices, 1970-2004



The general trend of prices has been downwards since the late 1970s, although average contract prices lagged behind. During the 1980s they were sustained by continuing deliveries under various fixed or cost-related price formulae negotiated during the early to mid 1970s. That was especially true of some US domestic purchases. The various measures of price have converged over the past two decades. TradeTech's exchange value is the most responsive indicator of prevailing market conditions, and has been more volatile than the other measures. With an important proviso about their massive surge and subsequent fall in the late 1970s and early 1980s, uranium prices have been less volatile than those of metals like copper that are traded on terminal markets. That is demonstrated by *Figure 4 <3>*.

Figure 4. Monthly average copper and uranium prices, 1970-2004

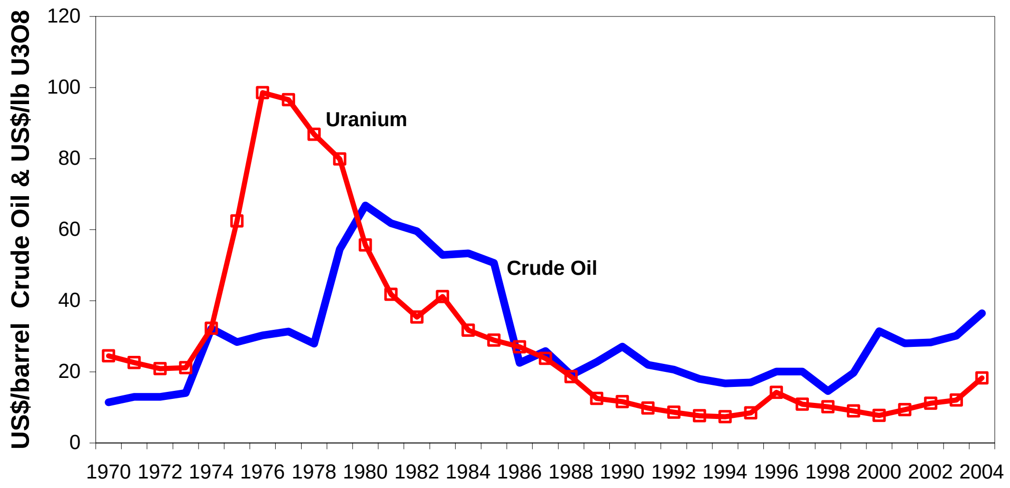


This apparent lack of volatility may largely reflect a continuing underlying excess supply, rather than any intrinsic feature of uranium. A beached whale is normally more subdued than one gambolling in the water. Even so, uranium has not been immune from the general political and economic conditions that affect all commodities. Since the commencement of civil applications of nuclear power the uranium market has witnessed three complete price cycles and is now into its fourth. The first occurred largely in the 1960s when the industry was adjusting from military to civil procurement. Prices rose by up to 60% in the late 1960s, only to subside in 1969-71 because of delays in reactor construction, the disposal of government stocks and general economic malaise. The second surge was partly triggered by the oil price rises of 1973-74 and the speculative furore that affected the prices of all commodities. Prices were forced up dramatically in the scramble for assured supplies of fuel for reactors that were often merely projected, let alone planned or under construction. The reaction during the early 1980s was almost as pronounced as the earlier surge. Delays and cancellations of nuclear power programmes coincided with increased mine supplies and the build-up of excess inventories. To a considerable extent the earlier price rise had carried the seeds of its own decline, a common result of surging prices in commodity markets <*4*>. The third price cycle, of the 1990s, was relatively brief and only subdued by the standard of the previous cycle. Prices rose to a peak in 1996-97 from their 1993-94 trough, with Nuexco's exchange value rising by 125% between July 1993 and July 1996, but soon subsided to new lows by the end of the decade. The rise was prompted by a production shortfall and a steady rundown of commercial inventories, and the fall by the mobilisation of military stockpiles for civil use.

The latest upswing has taken prices well above their 1996-97 peaks, and still displays strong momentum.

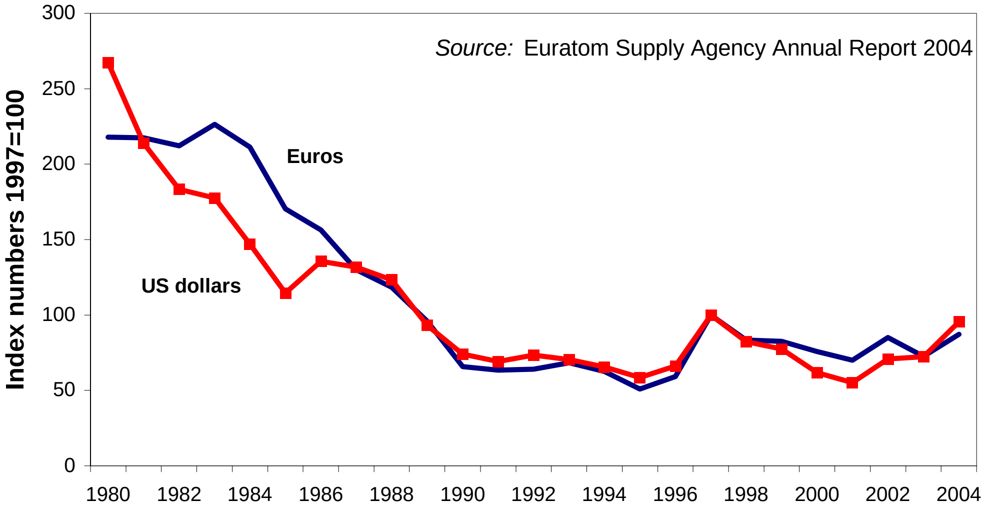
If the price rise of the mid 1970s was related to developments in the oil market, the subsequent relationship between oil and uranium prices has been fairly weak, as shown in *Figure 5* <5>. The recent rise in uranium prices has probably been influenced by developments in the oil market through changing market sentiment about energy supplies, but other influences have been much more important.

Figure 5. Uranium and crude oil prices in constant 2004 terms, 1970-2004



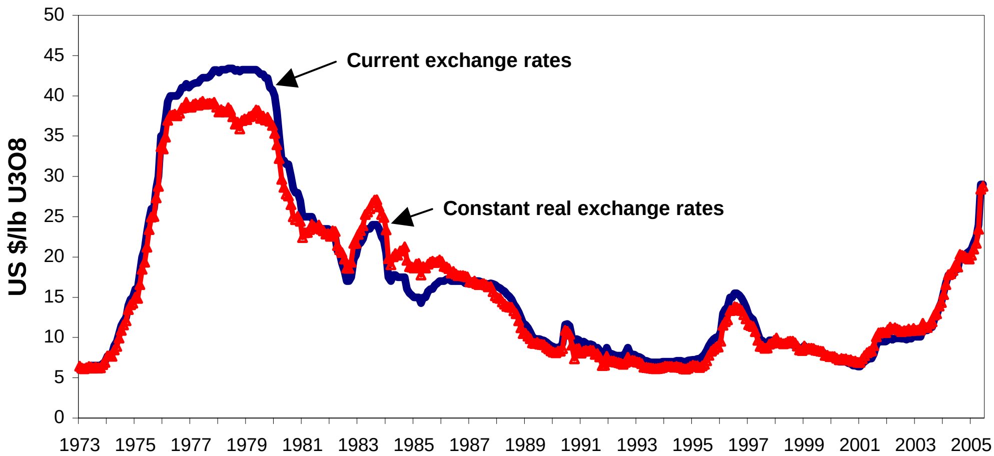
Unlike those of the earlier figures the prices of *Figure 5* are shown in constant dollars after adjusting for changes in price levels as well as shifts in the dollar's exchange rate. The latter have tended to accentuate the apparent swings in prices by varying the length of the dollar yardstick in which prices are conventionally quoted. A significant share of both production and usage of uranium incurs costs, or is priced, in currencies other than the US dollar. Euratom quotes average prices in both dollars and euros, and *Figure 6* shows, in index number terms, how spot prices moved in each currency since 1980.

Figure 6. Index numbers of Euratom annual average spot uranium prices in US dollars and euros, 1980-2004



Perceptions of the direction and extent of price movements differed in the early 1980s, and again in recent years, when viewed in the different currencies. Both the price surge of the late 1970s and the more recent rise partly reflect movements in the US dollar's exchange rate rather than any intrinsic behaviour of the uranium market. Strictly speaking, dollar prices should be adjusted by the value of the dollar against a basket of currencies of uranium producers and users to ascertain the precise impact of exchange rate changes, but approximate indications are given in *Figure 7*. This shows the impact of changes in the US dollar's real exchange rate against the currencies of the United States' trading partners on TradeTech exchange values <6>.

Figure 7. Nuexco/TradeTech unrestricted exchange values 1970-2004, showing the effect of changes in the US dollar's real exchange rate



A weakening of the US dollar accentuated the rise in prices in the late 1970s, and its subsequent strengthening contributed to falling uranium prices in the first half of the 1980s. Between May 1973 and May 1978 the exchange value rose by

573%, but the rise was a slightly more modest 502% at constant real dollar exchange rates. From May 1978 to May 1985 the exchange value fell by nearly 65%, with a fall of only 51% at constant real exchange rates. More recently, part of the rise in prices since early 2001 again mirrors a change in the US dollar's real value. The manner in which prices change in different currencies helps influence the way in which supply and demand respond.

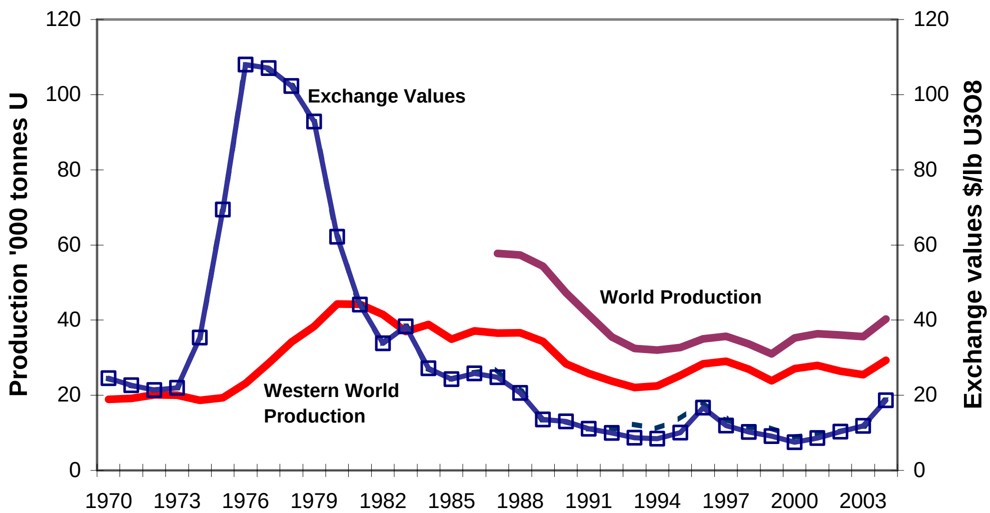
Supply responses

Although power utilities are mainly concerned about volume rather than price risk, and the main burden of price changes falls on supply, the demand for uranium is not completely price inelastic. Nor is it as boringly predictable as often assumed. The price of uranium concentrate may be only one influence amongst many in the pricing of fuel assemblies, but it is a factor. Changes in reactor efficiencies, load factors, enrichment levels and fuel burn up rates can all affect uranium requirements, even from a constant reactor capacity. Construction times for new reactors can be extended, especially when there are strongly competing claims on the resources of the construction and capital goods industries, and existing plants can suffer lengthy and unexpected outages.

Since the mid 1980s, rising reactor requirements have been partially met by the rundown of inventories amassed in earlier decades. These include not just the stocks acquired by power utilities to meet expected needs that never materialised, but also ex-military material. A consequence is that new mine production effectively became the marginal supplier until it accounted for only 55% of annual reactor requirements. In that regard uranium is not unique amongst mineral products. Mine production of gold fell to only 64% of global demand for gold for fabrication in 1997 from 93% in 1985, the balance coming from above-ground stocks <*7*>. The difference from uranium is that gold can act as a store of value and that very little is irretrievably used. Nonetheless, the impact of mobilising inventories on mine output and prices is very similar.

The relationship between uranium's spot prices and mine production is summarised in *Figure 8* <*8*>.

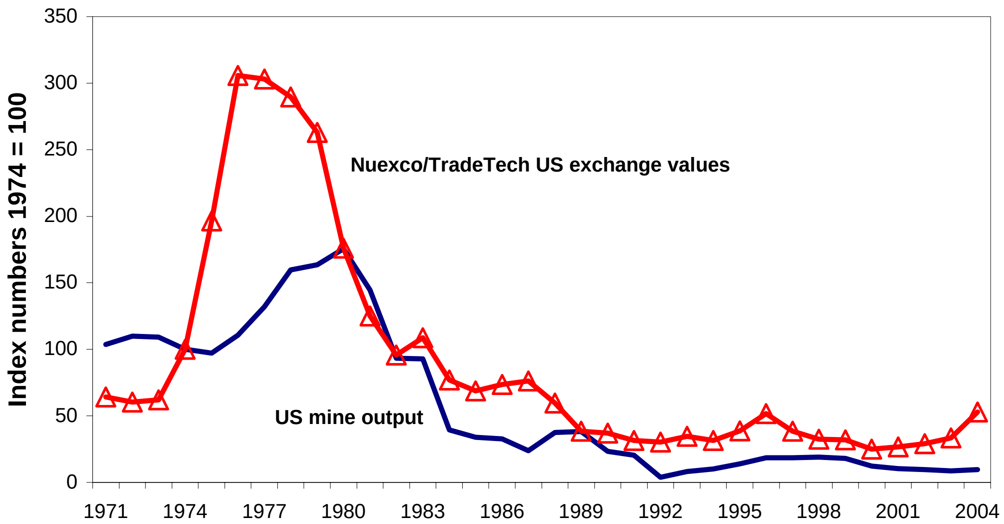
Figure 8. Uranium prices and mine production, 1970-2004



As with most mineral commodities, the collapse of the Soviet Union and the progressive integration of centrally planned economies into the global economy has created discontinuities in the data. *Figure 8* shows global output annually from 1987, and the production of Western world mines for the entire period. Changes in mine output tend to lag behind those of prices, but production clearly responds. In due course the price rises of the 1970s led to a 137% rise in output between 1974 and 1980, but output then declined with the weakening of prices, the exhaustion of some older deposits and the closure of higher cost mines. The nadir was reached in 1993, when Western output was down to roughly half its 1980 peak level. The price rises of 1996-97 had a discernible impact on mine output, but it was almost as temporary as the rise in prices. Production rose by 32% between 1993 and 1997, and then declined by 18% during the next two years.

The responsiveness of production to market conditions can be clearly seen in the United States whose uranium mining industry was well established before the development of civil reactor demand. *Figure 9* <9> compares US mine production with spot exchange values, both in index number form (based on 1974 as 100).

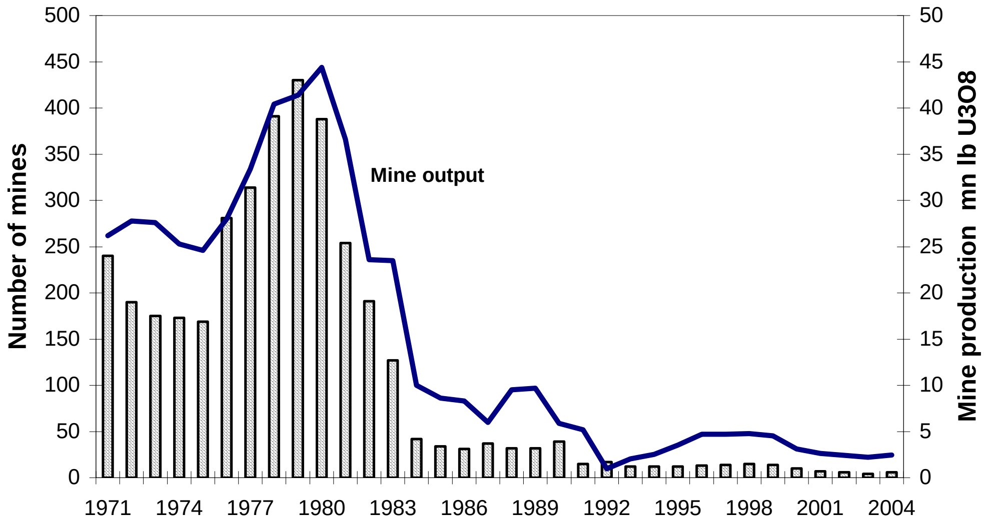
Figure 9. Index numbers of US prices and mine output of uranium



It took time for the 1974-76 price rise to work through to increased output. The initial effect was to allow mines to catch up on deferred maintenance and development work. Whereas ore throughput increased, the output of uranium concentrate fell as higher prices allowed the exploitation of lower ore grades. The output of concentrates then increased by 80% between 1975 and 1980, by which time prices had already turned down. The collapse in output in response to falling prices was dramatic, with output dropping to less than 1000 tonnes U by 1992, with only a modest respite in 1988-89. The revival of prices between 1992 and 1996 enabled a temporary recovery of production, but that was truncated by prices dropping back once more.

Behind the changes in mine output have been substantial changes in the number of operating mines, which have supplied a much smaller number of mills. These changes are illustrated in *Figure 10 <10>*.

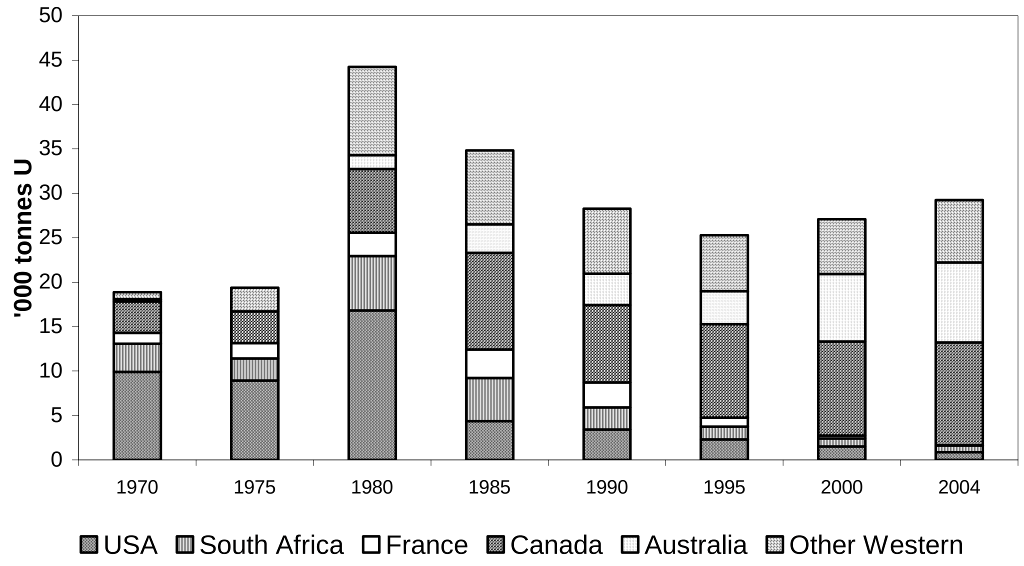
Figure 10. US uranium mine output and operating mines



Most of the mines were operating on a small scale and they were forced out of production by the changing uranium market conditions. The mills they supplied were also compelled to shut down by a mixture of shortages of feed and price-cost pressures. The US industry was unable to compete with lower cost sources elsewhere. Today only six mines are operating compared with 430 supplying over 20 mills at the end of 1979. No conventional mill was working at the end of 2004, with production mainly from in-situ leach plants.

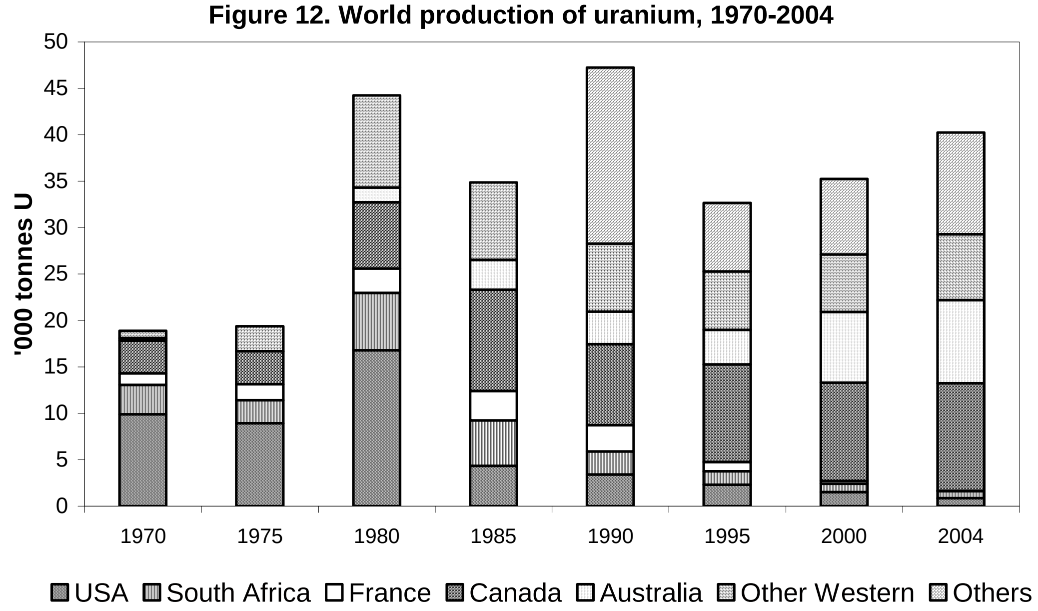
Although the decline of the US industry was the most dramatic it was by no means unique. The structure of the entire uranium mining industry has changed dramatically over the past thirty years, as shown by *Figure 11 <11>*. This gives the geographical distribution of mine output in Western countries at five-yearly intervals from 1970.

Figure 11. Western world uranium production, 1970-2004



The fall in US production between 1980 and 1995 alone accounted for just over three-quarters of the net decline over that period. In South Africa, where uranium is primarily a by-product of gold mining, rising costs and adverse exchange rate movements have forced the closure of gold mines, with adverse consequences for uranium production. Falling uranium prices also made recovery uneconomic, although all the mining costs are borne by gold. The drop in South African output equalled just over 26% of the net fall in Western uranium output between 1980 and 1995. French production, which was effectively state-supported has also dwindled to insignificance. The main gainers have been Australia and Canada whose present operations are larger and lower cost than the earlier generation of mines. There have been changes within the 'Others' category, most notably with the cessation of mining in Gabon in 2000. Changes in Niger and Namibia have been largely market-related, and are reversible. *Figure 12* adds production from other countries from 1990 onwards to show changes in global output.

Figure 12. World production of uranium, 1970-2004



Mines closed in some Central European countries after the collapse of communism, and they are unlikely to re-open because of their high costs of all types, including their environmental impacts. Production from CIS countries has, however, recovered and will continue to do so.

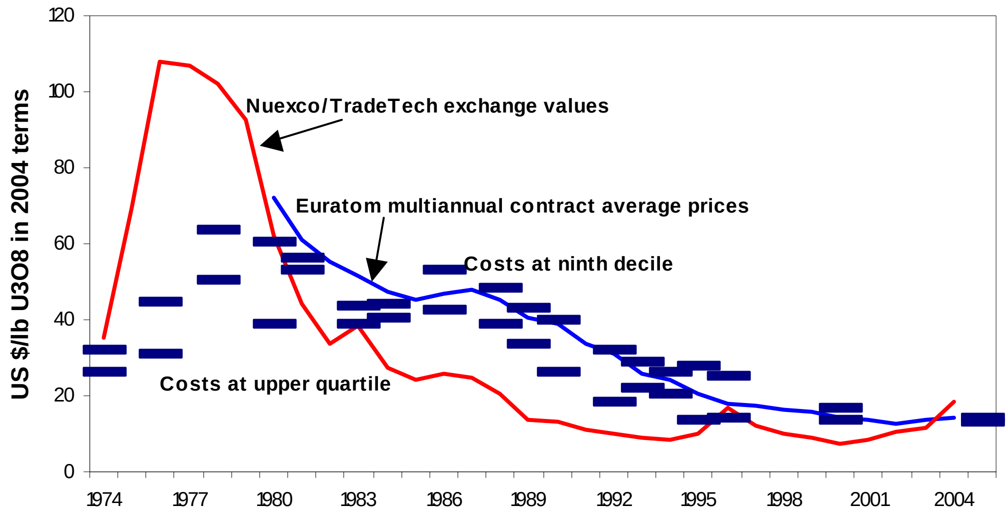
Historic trends may be interesting, but they are only illuminating to the extent that they offer guides to the future. Whereas US and French output is highly unlikely to regain its previous levels, there are many known uranium deposits that are underdeveloped or unexploited. Today's list of such deposits is very similar to one that might have been drawn up twenty five years ago. That does not mean that they will all be developed, certainly on a timely basis, if at all, for a variety of technical, economic and political reasons. In that regard uranium is no different from other minerals.

The mines that closed over the past thirty years either ran out of economically exploitable ore, or they became too high cost to continue operating. Some still have ore that could be extracted if prices remain reasonably buoyant, but in most instances surface facilities have been dismantled and sites cleared. The experience of the 1970s in re-opening mines that had closed during the late 1950s and 1960s demonstrated the costs involved in bringing mines back into production, even where they were nominally on care and maintenance. Mines have to be adapted to accommodate modern mining equipment and to meet today's health and safety standards, and that can be more expensive than building new mines. Many of the mines that shut are lower grade, and intrinsically higher-cost than the present generation of mines. That does not completely rule out their resurrection, but it does make it more difficult.

Production costs

Mining companies did not passively accept weakening prices and markets without aggressively responding with innovative methods and cost reductions. Most new mines perforce had lower costs than those they replaced. This was partly because improved geological understanding of the genesis of uranium ore-bearing rocks had directed exploration to much higher grade deposits than those exploited up to the 1970s. *Figure 13* shows how the marginal costs of uranium mining moved relative to prices over the past thirty years <*12*>.

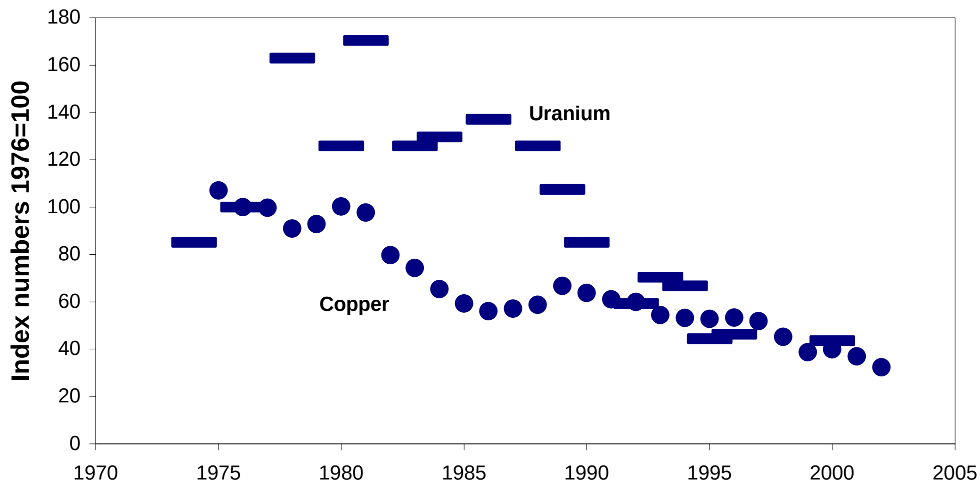
Figure 13. Uranium prices and costs, 1974-2004



Throughout the mining industry there is a strong tendency for prices to move in step with marginal cash costs, as shown in *Figure 13* by the costs at the upper quartile and ninth decile. Prices can soar above this cost floor in buoyant markets, but they bump against the cost floor when conditions are depressed. In uranium's case the existence of other sources of supply have enabled spot prices to persist well below cash costs for an extended period. Prices have, in effect, fallen through the cost floor to the basement. Euratom's annual average multi-annual contract prices have, however, followed the general rule by tracking costs. Weak prices force out high cost operations and encourage cost cutting.

Uranium has followed a general mining industry trend in witnessing a flattening of the cost curve over the period. That is illustrated here by the narrowing of the gap between the two levels of cost. In passing, the inclusion of all sources of supply, including ex-military material, would only slightly reduce marginal costs in 2002, but it raises them considerably for 2005. Such material is processed for strong political and strategic rather than economic reasons. Over the entire period from the mid 1970s to the early 2000s the marginal cash costs of uranium mining have dropped in real terms by roughly the same extent as those of other minerals such as copper <*13*>. Unlike copper, however, the uranium industry saw rising costs in the late 1970s and early 1980s as production expanded. The comparison is made in *Figure 14*.

Figure 14. Index numbers of upper quartile copper and uranium costs, 1974-2002

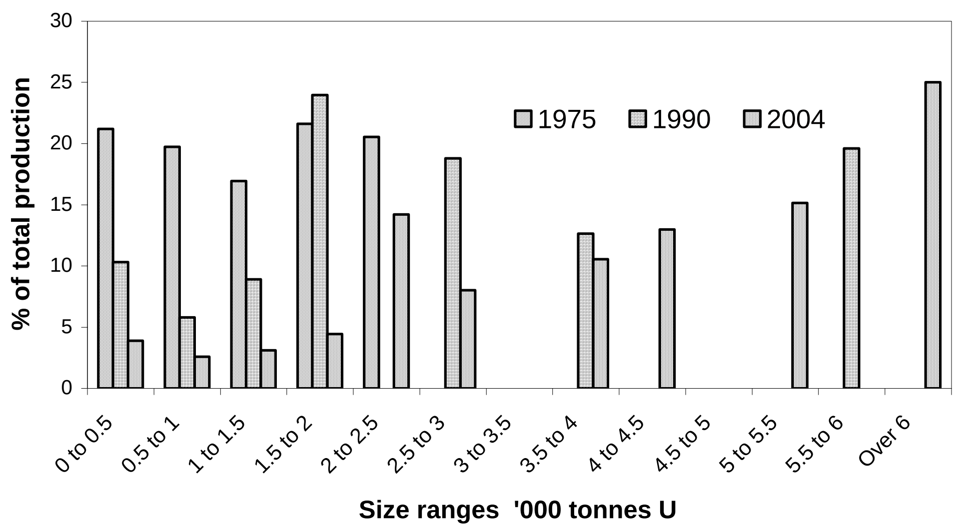


There is no absolute guarantee that technical innovation and rising productivity will continue to restrain mining costs. Nonetheless, any projections of costs, and by implication prices, that fail to allow for the possibility will probably overstate future prices, perhaps by a large margin.

The corporate structure of uranium mining

One of the main drivers of falling real cost throughout the mining industry has been the exploitation of economies of scale. The closure of the many small US mines is one instance. *Figure 15* shows how the size distribution of uranium producing facilities in the Western world has changed over the past thirty years *<14>*.

Figure 15. Size distribution of uranium production facilities, 1975-2004



Whereas all production came from facilities with a capacity of less than 2500 tonnes U in 1975, such facilities accounted for only 49% of output in 1990 and 28% in 2004. By then just over 40% of Western world output came from facilities producing more than 5000 tonnes U per annum <*15*>. When allowance is made for the uranium mines of China and the CIS countries just over 26% of 2004 output came from mines producing 2500 tonnes U, or less, and 31% from mines producing 5000 tonnes or more. Whilst the revival of uranium mining in coming years will involve the opening of mines across the size spectrum, the average scale of operations should continue to increase, particularly with any major expansion of Olympic Dam. That seems highly probable, given the price paid for its acquisition. Across all minerals over the past fifteen years, investment in new capacity has invariably followed the acquisition of assets, sometimes in defiance of market conditions.

The scale of production facilities may affect costs, but it is not necessarily a guide to the concentration of their ownership. In that regard, *Figure 16* shows how the concentration ratios, the shares of output controlled by leading firms, have altered over the past thirty years <*16*>.

Figure 16. Percentage shares of uranium mine output controlled by leading firms, 1975-2004

	1975	1984	1994	2004	2004
	Western world				World
Leading producer	10.3	11.9	23.9	27.7	19.8
Three largest companies	29.6	31.8	49.7	72.2	51.6
Five largest companies	43.3	45.0	61.9	89.1	69.3
Ten largest companies	64.4	65.2	83.8	99.7	89.0

Source: Raw Materials Group database

There has been a significant increase in concentration over the period, largely reflecting the closure of smaller operations and the increased scale of the remaining mines. State-owned companies and oil producers controlled a significant share of output in the 1970s and 1980s. Whereas the latter have faded from the scene, as they have in other sectors of mining, state-owned companies are still involved, although by no means to the same extent. The identity of the leading producers has changed over the period. The global industry is today more concentrated than Western world production a decade ago. Whilst new producers will probably start up over the coming years, the degree of concentration is unlikely to diminish significantly. Much of any increased output will initially come from established producers.

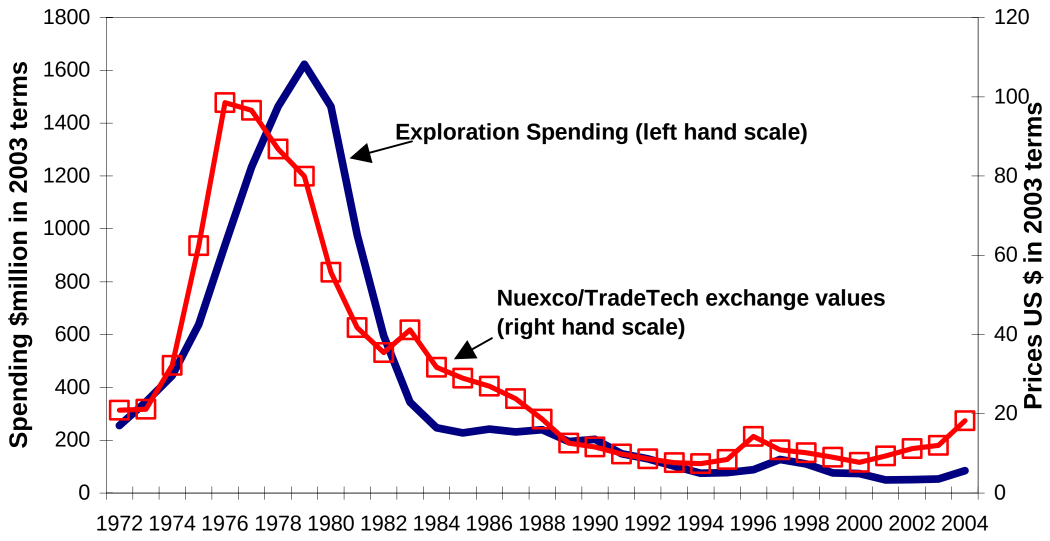
Although the uranium industry’s degree of concentration is greater than for many minerals, the leading producers’ ability to influence pricing is constrained by continuing sales from inventory and ex-military material. Moreover, they are selling to a relatively limited number of powerful utilities.

Exploration

The recent recovery of prices has attracted renewed interest in uranium, which had fallen off the exploration map for a considerable period. As in the late 1970s, much of the rise in prices has been speculative, based on expectations of renewed interest in nuclear power, and the exhaustion of previously mined commercial inventories. These expectations have some substance, but carry the seeds of another downturn. Several existing producers have the scope, and probably the inclination, greatly to expand their output. The disposal of ex-military material and other government-owned stocks will continue. The lobbying power of the US uranium mining industry to inhibit such disposals has dwindled to insignificance. There is a range of undeveloped deposits discovered in the exploration boom of the 1970s and 1980s that still await development. To the extent that their owners expect prices to persist at present levels, let alone rise further, some of these deposits will be developed. Once they are in production, their full costs become irrelevant, and they will produce as long as they can cover their much lower operating costs. On the demand side, higher prices encourage increased efficiencies of fuel use. The lead times for planning and constructing new reactors remain considerable, even when there are no permitting obstacles. Public opinion remains antagonistic in many countries, notwithstanding arguments about climate change, rising prices of conventional fuels or opposition to unsightly wind farms. Few political leaders have the willingness or necessary courage to make the case for nuclear plants that will seldom go on stream during their periods of office.

None of these arguments will quickly discourage speculative interest. As past experience demonstrates, rising prices greatly influence exploration spending. *Figure 17* compares Western world exploration spending in real terms <*17*> with spot prices over the period since 1972.

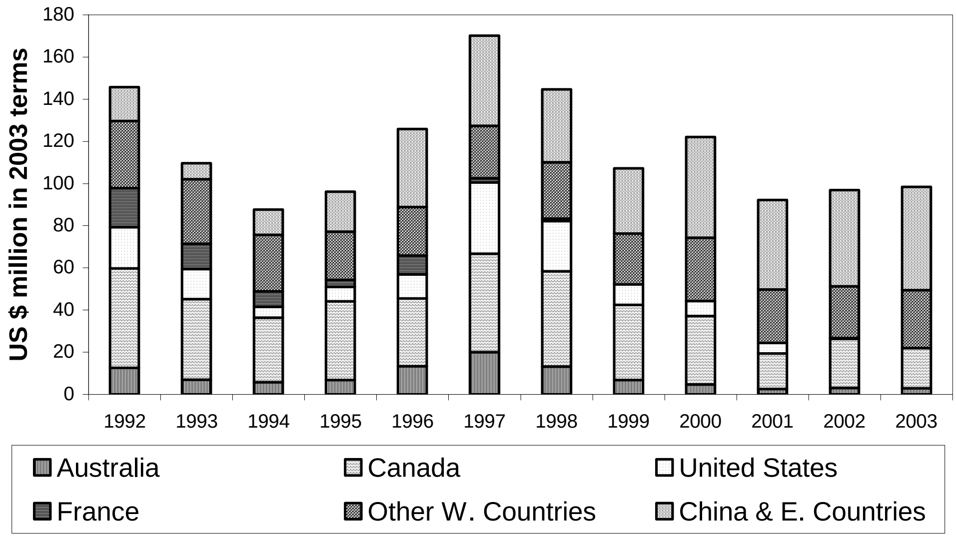
Figure 17. Uranium exploration spending & prices
Western world, 1972-2004



Exploration spending has lagged behind changes in prices, but has tracked them closely, even during the brief cycle of the 1990s. The latest price rises are already being reflected in renewed exploration spending. In 2004 it rose by roughly twothirds in both Australia and Canada, and in the United States some $10 million was spent after virtually nothing in 2003. Uranium competes with other target minerals for exploration resources, including skilled manpower. During the 1980s and early 1990s the main target was gold, and more recently there has been strong interest in diamonds. That uranium exploration has increased even more than exploration for other minerals emphasises the strength of the present interest.

The huge boom in spending of the late 1970s and early 1980s resulted in many discoveries, but a substantial proportion was unproductive. Much was funded by governments with a strategic imperative, and still more was directed towards only modest targets in the United States. In 1979-80, roughly 58% of exploration spending in the Western world was in France and the United States. As *Figure 18* demonstrates <*18*>, neither country was even a minor target by 2003.

Figure 18. World expenditure on uranium exploration, 1992-2003



During the past twenty years uranium exploration has been at a virtual standstill, except near known occurrences. Exploration techniques and geological understanding have continued to improve during that period, and the political landscape has been transformed. Exploration can now be more precisely directed to prospective areas, and is therefore likely to be more productive than in the past. In recent years an increasing share of exploration spending has gone towards Kazakhstan, China and Russia, whilst Australia and Canada have continued to excite interest. It is impossible to state how successful future exploration will be, but it is as well to be extremely wary of any claims that are advanced about future scarcity of resources or the relative importance of any presently known deposits. They are invariably made by those with special interests of one form or another. Spinning is not confined to New Labour politicians.

Concluding comments

What conclusions can be drawn from this ramble around aspects of the past thirty years' history of the uranium industry? First, uranium supply is responsive to price signals, both when prices are weakening and when they are rising. There is an interplay between prices and costs that works in both directions. Secondly, uranium mining has not operated within a vacuum, and it has shared many of the characteristics of other types of mining over this period. Thirdly, the geographical and corporate structure of the mining industry has altered irrevocably, but with no unequivocal indications for future prices. Finally, there is a strong tendency for prices to overshoot their equilibrium level, both in weak markets and in boom periods. Undershooting has been far more pronounced in uranium than in most other minerals because of the existence of considerable inventories of previously mined materials. These have been only partly exhausted, and ex-military materials will still be diluted and released into the civil market for strong political reasons. Nonetheless, there is a growing need for increased mine output to meet the requirements of existing reactors, let alone any new generation. The resources to meet that demand are already known, and rising exploration will discover more. There is a strong probability that speculative pressures, which are already evident, will push prices too high and sustain them for longer than is needed to ensure long-term equilibrium. Those who hold on to uranium in the expectation of higher prices are carrying considerable risks. There is no futures market for uranium in which to hedge prices, and holders are likely to offload as soon as prices weaken, thereby exaggerating any downturn. The foundations of the next uranium price cycle are already in place.

Notes and References

1. R. M. Williams. Uranium Chapter of the Canadian Minerals Yearbook 1975, Canadian Department of Energy, Mines and Resources.

2. The Euratom annual average multi-annual and spot prices are from Euratom Supply Agency Annual Report 2004, Brussels 2004. The US annual average prices are weighted averages of domestic purchases and purchased imports. For 2003-04 they are from the Uranium Marketing Annual Survey (Energy Information Administration Form EIA-858), for 1981-2002 from Table 9-3. Uranium Overview, from the Annual Energy Review 2003 (DOE/EIA 0384/2003), Washington DC September 2004, and for years before 1981 from successive issues of the Uranium Industry Annual (Energy Information Administration, Washington DC). The Nuexco/TradeTech exchange values are annual averages of the monthly unrestricted values published on the TradeTech website (www.tradetech.com).

3. Monthly average cash settlement prices for Grade A copper cathodes from the London Metal Exchange, with sterling prices up to 1993 converted to US currency at monthly average sterling/dollar exchange rates from the US Federal Reserve Board's Statistical Release G5. (www.federalreserve.gov/releases/g5). The uranium prices are Nuexco/TradeTech end-month exchange values in unrestricted markets (www.tradetech.com).

4. See Phillip Crowson, Uranium as a commodity; lessons for the future, in Uranium and Nuclear Energy: 1985, Proceedings of the Tenth International Symposium, The Uranium Institute, London 1985.

5. The uranium prices are Nuexco/TradeTech end-month exchange values in unrestricted markets (www.tradetech.com). The crude oil prices are weighted average values from the International Monetary Fund's World Economic Outlook Database (www.imf.org). Both price series are deflated to constant 2004 terms with the United States' implicit GDP price deflator (2000 = 100)

(www.bea.gov/bea/dn/nipaweb), and adjusted for changes in the real exchange rate of the US dollar, using the US Federal Reserve Board's price-adjusted broad dollar index (www.federalreserve.gov/releases/H10/Summary/indexbc_m.txt).

6. The prices and exchange rates used for *Figure 7* are those outlined in the preceding note.

7. Data from Gold Fields Mineral Services Limited, private communication October 2004.

8. Nuexco/Tradetech exchange values in real 2004 terms are used as the indicators of spot prices. The broken line shows the US/restricted values where they differ from the unrestricted values. Money values have been deflated to 2004 terms with the US implicit GDP price deflator (see note v). Mine production of uranium derived from successive issues of the OECD/IAEA Red Books on Uranium Resources, Production and Demand, plus more recent data from the World Nuclear Association website.

9. The index numbers are based on Nuexco/TradeTech exchange values for US/restricted markets deflated to 2004 terms (see note 7), and US mine production of uranium concentrate. That differs slightly from concentrate output. The data are from successive issues of Statistical Data of the Uranium Industry (GJO-100), published by the DOE, up to 1981, from successive issues of Uranium Industry Annual (DOE/EIA-047), published by the Energy Information Administration, Washington DC, for 1982-2002, and from Domestic Uranium Production Report, Energy Information Administration Form EIA-851A for 2003-04.

10. The data on mine numbers are from the same sources as mine output, as described in note 9. Separate figures are given for open-pit, underground, in-situ leach mines, and other sources, including phosphate and copper by-product sources. The scope of the latter may have varied slightly from one year to the next.

11. Data from the sources given in note 8.

12. The data underlying *Figure 13* are drawn from a wide variety of sources. The prices are from the sources listed in notes 2 and 5. The estimates of cash costs are for mines operating in the relevant years. They exclude any element of profit or capital recovery, merely covering all the operating expenses of producing uranium concentrates. The cost of any royalties or taxes that are based on levels of production or turnover are included, but not any profit-related taxes or royalties. Costs are converted to US dollars at the exchange rates prevailing in the relevant years, and they are then adjusted to 2004 terms with the US implicit GDP price deflator. The figures for 1974-1996 are from the Rio Tinto Mine Information System (private communication), and those for 2000 and 2005 are derived from NAC International's Uranium Supply Analysis. In all instances the data refer only to mines in the Western world, and they exclude any supplies from existing stocks of any type. Thus they do not fully reflect the marginal costs of supply in the past two decades. For each year mines are ranked in ascending order of cost to produce curves of costs plotted against cumulative production. The costs 75%

(the upper quartile) and 90% (the ninth decile) along the cumulative production are then extracted.

13. The data on cash costs of copper mining in *Figure 14* are from continuing annual surveys carried out by Brook Hunt Associates (defined as C1 composite costs in the surveys). The index numbers are based on cash costs at the upper quartile, as defined in note 12, in constant US dollar terms. Money values are deflated with the US implicit GDP price deflator.

14. The data underlying *Figure 15* are derived from the proprietary online Raw Materials Database maintained by the Raw Materials Group, Stockholm, Sweden. For the United States they are based on mills rather than individual mines, so that the unit size is larger and the number much fewer for 1975 and 1990 than indicated by the data of *Figure 10*.

15. The rise in scale of uranium mines is similar to that of other mineral commodities. See Phillip Crowson, Mine Size and the Structure of Costs, Resources Policy 29 (2003) pp 15-36.

16. The data are derived from the same source as *Figure 15* (see note 14). The effective control of production is determined not by equity shares but by taking complicated corporate structures into consideration. For example, a company may have over 50% of the voting shares, or it may be the largest shareholder with 40% of the shares, or it might be one of several large shareholders but also have management control of the company, or two companies may hold large positions in a mine, but in turn those two companies may be controlled by the same parent. The important aspect is who is making the decisions.

17. The estimates of exploration spending are taken from the OECD/IAEA Red Books on Uranium Resources, Production and Demand (OECD Paris, successive issues to 2004). Spending in current dollars has been deflated to real 2003 terms with the US implicit GDP price deflator (see note 5). The figures for 2004 are estimates based on actual figures for the USA, Canada and Australia. The US data are from Domestic Uranium Production Report, Energy Information Administration Form EIA-851A for 2003-04. The Canadian are from Natural Resources Canada (http://mmsdl.mms.nrcan.gc.ca/mmsd/exploration). Australian data are taken from Table 5 of Publication 8412.0 of the Australian Bureau of Statistics, Canberra, June 2005 edition. The indicator of prices is the Nuexco/TradeTech exchange value in unrestricted markets, deflated to 2003 terms.

18. Same source as *Figure 17* (see note 17).

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