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Nuclear Fuel: A New Market Dynamic

After almost 20 years of low nuclear fuel prices, buyers have come to expect that these low and stable nuclear fuel prices will continue. This conventional wisdom may not reflect the significant changes and higher prices that growing demand, and the end of secondary sources of uranium and enrichment, will bring.

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I. Introduction

The world output of nuclear electricity has been steadily growing and has created a growing demand for nuclear fuel.

The first complete filing of a Combined Construction and Operating License Application ("COLA") for the South Texas Project expansion was presented to the US Nuclear Regulatory Commission ("NRC") on 25 Sept. 2007. Constellation filed the environmental section of a COLA for their planned new Calvert Cliffs unit a few months earlier and at the end of October, TVA filed a COLA for 2 new units to be built at the Bellefonte site. These COLA filings are the first of many, as US nuclear project developers compete for the first-come, first-served benefits of the Energy Policy Act of 2005 and start a new wave of nuclear power plant development in the US. Outside the US, countries have either continued to build nuclear plants or are now embarking on plans, some very ambitious, for new nuclear power plants.

As the next generation of new nuclear plants procure initial fuel core loads and enter commercial operation over the next 10 to 20 years, the demand for nuclear fuel will grow significantly. There is wide consensus that there is sufficient nuclear fuel for this world-wide expansion of nuclear power, based on the amount of known and likely uranium reserves. However, the pace at which these reserves are converted into producing mines depends on markets and the response of uranium miners to market incentives.

Depressed prices in the uranium market have meant that world production of uranium has declined, with primary uranium supply below demand since 1990. This shortfall in uranium supply has been met by secondary sources consisting of stockpiles of uranium from past periods when production exceeded demand, including the blending down of existing military stockpiles of highly-enriched uranium ("HEU"). Likewise, a significant portion of enrichment demand has been met by these HEU blend down arrangements. The markets for both uranium and enrichment, reflecting this dependence on secondary sources, have not reached supply and demand equilibrium.

Meeting the long-term demand for uranium and enrichment services will depend on finding and developing new uranium mines and on building new enrichment facilities, both of which will take time and require significant capital investment. This investment will only occur if prices for uranium and enrichment are at or above long-run marginal cost. Importantly, the development of new facilities will take more than a decade to reach full production, so that the nuclear fuel market will remain in a transition period even as the first wave of new US nuclear plants are procuring initial core fuel loads and entering commercial operation.

During the adjustment period between the current situation and long-run equilibrium between supply and demand for uranium and enrichment, there is a possibility that nuclear fuel costs will be higher and more volatile and even the potential for temporary shortages. This adjustment period has already started, as highlighted by the increase in uranium spot prices below \$20/lb in mid-2004 to a new all-time high price of \$138/lb in July 2007.

Uncertainty about nuclear fuel costs comes at a time when decisions are being made to build new nuclear power plants.

Uncertainty about nuclear fuel costs also comes at a time when decisions are being made to build new nuclear power plants. Nuclear plant developers, facing large and urgent issues associated with licensing, construction costs, and related matters, may view nuclear fuel costs as less important and less urgent. However, while the cost of nuclear fuel represents a small part of nuclear electricity production costs, nuclear fuel cost increases can have a pivotal effect on nuclear project economics, especially when estimates of nuclear option lifecycle costs do not differ much from the lifecycle costs of alternatives such as conventional coal or IGCC plants.

II. The Nuclear Fuel Cycle

Unlike most electricity generation fuels, nuclear fuel is a complicated product.[1] Uranium ore is the feedstock in a complex multi-stage process, known as the 'front end' of the nuclear fuel cycle, to manufacture highly-engineered nuclear fuel assemblies that are designed to be loaded into a specific power reactor core. This involves mining, processing and milling, conversion, enrichment, and fuel assembly fabrication.

The first step in producing nuclear fuel is mining uranium ore. Mined uranium ore is then sent to a processing plant or mill, usually located near the mine, where refined uranium oxide (U308), known as yellowcake, is extracted from the ore.

Yellowcake is shipped to a conversion plant where it is converted to uranium hexafluoride (UF6) in preparation for enrichment.[2]

Natural uranium consists of three isotopes, uranium 238 ("U-238"), uranium 235 ("U-235") and trace amounts of uranium 234. Natural uranium is only about 0.71% U-235. Because most nuclear power reactors are designed to use nuclear fuel that contains 3% to 5% U-235, natural uranium must be enriched in order to increase the U-235 concentration.

Because U-235 and U-238 have similar chemical properties, uranium enrichment processes exploit the extremely small mass difference between these two isotopes (i.e., U-238 atoms are a little heavier than U-235 atoms).

Fuel fabrication facilities convert enriched UF6 into uranium dioxide (UO2) powder that is sintered into small pellets and loaded into fuel tubes made of Zircaloy or other fuel cladding material. The fuel tubes are joined together in a framework called a fuel assembly that is designed for a specific location in a specific reactor core. Nuclear fuel may also include burnable poisons[3] and various levels of fuel enrichment to optimize core power density, maximize fuel burnup, and extend the refueling cycle.

Fuel assemblies are loaded into a power reactor, either at initial fuel load where the entire core is loaded, or at a subsequent refueling outage, where about a third of the fuel assemblies are replaced.

A reactor with an output of 1,000 MWe has a core with more than a hundred nuclear fuel assemblies, depending on type and design, and contains about 75 metric tons ("tonnes") of uranium.

During power operation, nuclear fuel rods produce heat from fission that is used to produce steam. This steam drives steam turbines and generates electrical power. As the reactor plant generates power, the U-235 content is decreased and fission products are formed.[4]

Used nuclear fuel assemblies are removed during each refueling outage and replaced with fresh fuel assemblies. The entire set of fuel assemblies is removed when the reactor is decommissioned at the end of operating life.[5]

Countries without any nuclear power history are now seriously considering nuclear plants.

III. Demand for Nuclear Fuel

The world nuclear power industry has performed well over the past decade or more. The world output of nuclear electricity has been steadily growing as a result of power uprates, life extensions, and higher capacity factors at existing nuclear power plants. European countries have reversed earlier plans to phase out nuclear plants or are considering doing so. This increased performance has led to steady growth in the demand for nuclear fuel.

The development of new nuclear power plants has started in the US. Other countries with existing nuclear power plants, including Japan, China, France, South Korea, India, South Africa, Finland, and Russia, have either continued the development of new nuclear plants or are embarking on ambitious new plans. Countries without any nuclear power history are now seriously considering nuclear plants. Countries that have relied upon fossil fuels for electricity generation are now considering nuclear power, even in regions where oil and gas are plentiful. Several countries in the Persian Gulf region, including Yemen and Jordan, have expressed interest in developing nuclear power as a source of electricity generation and water desalination. Research and development into new reactor technologies that will produce hydrogen is proceeding.

The primary driver of future nuclear fuel demand is the global expansion of nuclear power plants. Currently, there are more than 20 nuclear power plants under construction around the world, at least 60 more in the planning stages, and even more under consideration. Over the period from the end of 2005 to 2015, total net nuclear plant capacity in operation is expected to increase by 36 to 72 GWe, with an additional 40 to 90 GWe expected to be added between 2015 and 2025.[6] This nuclear generating capacity growth will result in an increase in the demand for uranium over the period from the end of 2005 to 2015 by 7.8 to 16.5 thousand tonnes per year with an additional 7.6 to 17.4 thousand tonnes per year added between 2015 and 2025. [7]

If the experience with the timing, construction cost and performance of the next generation of new nuclear plants is good, the second wave of nuclear power expansion may be even greater than current projections and will drive even higher demand for nuclear fuel

IV. Nuclear Fuel Cost

The primary advantage of nuclear electricity is the low cost of nuclear fuel. Low nuclear fuel cost provides benefits over the operating life of a nuclear plant that offsets the high initial capital cost and the high annual fixed O&M cost of nuclear plants as compared to conventional coal or natural gas generation. In the US in 2006, average nuclear electricity production cost (i.e., operations and maintenance costs plus fuel costs) of $17.2/MWh was lower than electricity production costs from coal generation ($23.7/MWh).[8]

The 2006 nuclear electricity production cost advantage is based on a nuclear fuel cost of $4.6/MWh. Nuclear fuel cost has been declining for some time, reflecting the historical low cost of uranium and increased nuclear plant output between refueling outages (i.e., the cost of fuel is amortized over more MWh). At uranium prices of $100/lb or higher, nuclear fuel cost would increase to more than $10/MWh, increasing nuclear electricity production costs to levels greater than the production cost from coal.[9]

Nuclear fuel costs are relatively low and are a small part of the total cost of electricity from nuclear power stations, so that nuclear fuel cost increases are unlikely to change the role of nuclear plants as baseload generators. While fossil-fueled generating units are dispatched down or turned off when fuel costs are high to limiting financial exposure to high fuel costs, nuclear units are consistently dispatched as base load or even must-run resources.[10] This means that any increases in nuclear fuel prices will reduce profits from new merchant (i.e., non-regulated) nuclear power plants and lower benefits to regulated utility owners of new nuclear plants.[11]

There is a large amount of uranium in the world, but it is widely dispersed and is usually found in low concentrations.

Some regions in the US have had consistent load growth with little new investment in baseload generation for the past decade. The primary options for adding new baseload are coal and nuclear. When the long-run economics of these two options are compared, the result is usually close; small changes in assumptions, including those for nuclear fuel cost, can change the preferred option.

The cost of uranium and enrichment make up about 75% of nuclear fuel cost, assuming 2006 prices for nuclear fuel cycle components. These two components are also the most likely to have high and volatile prices as the nuclear fuel market adjusts to higher demand without secondary sources.

V. Uranium

There is a large amount of uranium in the world, but it is widely dispersed and is usually found in low concentrations. Depending on the assumptions used, there is enough uranium to meet the needs of the nuclear power industry for nuclear fuel for hundreds of years, even if uranium is the primary fuel in a once-through fuel cycle.[12]

The Nuclear Energy Agency ("NEA") of the Organization for Economic Cooperation and Development (OECD) and the International Atomic Energy Agency (IAEA) in 2005 produced the latest of a series of reports known as the 'Red Book' on uranium resources. The 2005 Red Book concluded that uranium resources are adequate to meet the needs of both existing and projected nuclear power plants worldwide.[13]

The Red Book divides uranium reserve estimates into categories according to level of confidence and estimated production cost. The uranium reserve category with the highest confidence is Reasonably Assured Resources ("RAR"), consisting of uranium reserves in known deposits that could be recovered with currently proven mining and processing technology at specified production cost levels. [14] 2005 RAR at costs up to $130/kgU amounted to 3.3 million tonnes of uranium.

RAR amounts and production cost levels are not intended to represent a world uranium supply curve, as estimated reserve amounts may be well below actual recoverable uranium and estimated production costs may be well below the prices that a commercial miner might require to actually explore and develop a producing uranium mine.

Low uranium prices since 1985 meant that only a few mines with low production costs could remain in operation. By 2005, primary uranium production was about 41 thousand tonnes, only 60% of world uranium demand of about 68 thousand tonnes.[15] There has been some increase in uranium production since 2004, but a significant part of world uranium demand is met by secondary sources that include:

- Inventories of previously mined and processed uranium ore
- Inventories of HEU produced for military programs in the US and in Russia
- Inventories of uranium enrichment tails, also known as depleted uranium, with a relatively high tails assay (e.g., 0.25% to 0.35% U-235), that could be enriched to a lower tails assay

The potential long-term supply of uranium or plutonium is more than sufficient, but the timing and price of these supplies is uncertain.

- Inventories of spent fuel stored as complete fuel assemblies that could be reprocessed to produce recovered uranium and plutonium for use in mixed oxide ("MOX") fuel
- Inventories of surplus weapons plutonium that could be converted to MOX fuel

Uranium-based secondary sources depend on stockpiles of mined uranium ore and HEU that are being drawn down as demand and prices increase. The Russian HEU arrangements are scheduled to end in 2013 and while still available to meet world demand after 2013, any remaining Russian HEU will be dedicated to producing nuclear fuel to supply Russia's existing and planned nuclear power plants.

The World Nuclear Association's 2005 market report suggested that secondary sources would be largely depleted by 2015 and that only the uranium demand in the low growth scenario would be met by existing and known new uranium mines.[16]

While uranium-based secondary sources are expected to be depleted by 2015, there is potential that the use of plutonium-based MOX nuclear fuel will increase. As the price of uranium-based nuclear fuel increases, the economics of reprocessing spent fuel to produce MOX fuel will become more attractive.[17] There are also efforts underway, driven by policy reasons rather than commercial economics, to dispose of surplus weapons plutonium by converting it into MOX fuel for use in commercial reactors.[18]

The potential long-term supply of uranium or plutonium for nuclear fuel is more than sufficient, but the timing and price of these supplies is uncertain.

Figure 1 shows uranium spot prices since 1948, in nominal prices and in 2007 inflation-adjusted prices. This Figure shows that uranium spot prices have experienced 3 spikes since 1948.

The first spike, in the 1950s and 1960s was the result of the US Atomic Energy Commission ("AEC") purchase arrangements and prices, as the US Government sought uranium for military purposes. As US Government uranium stockpiles were built up, the AEC phased out its uranium

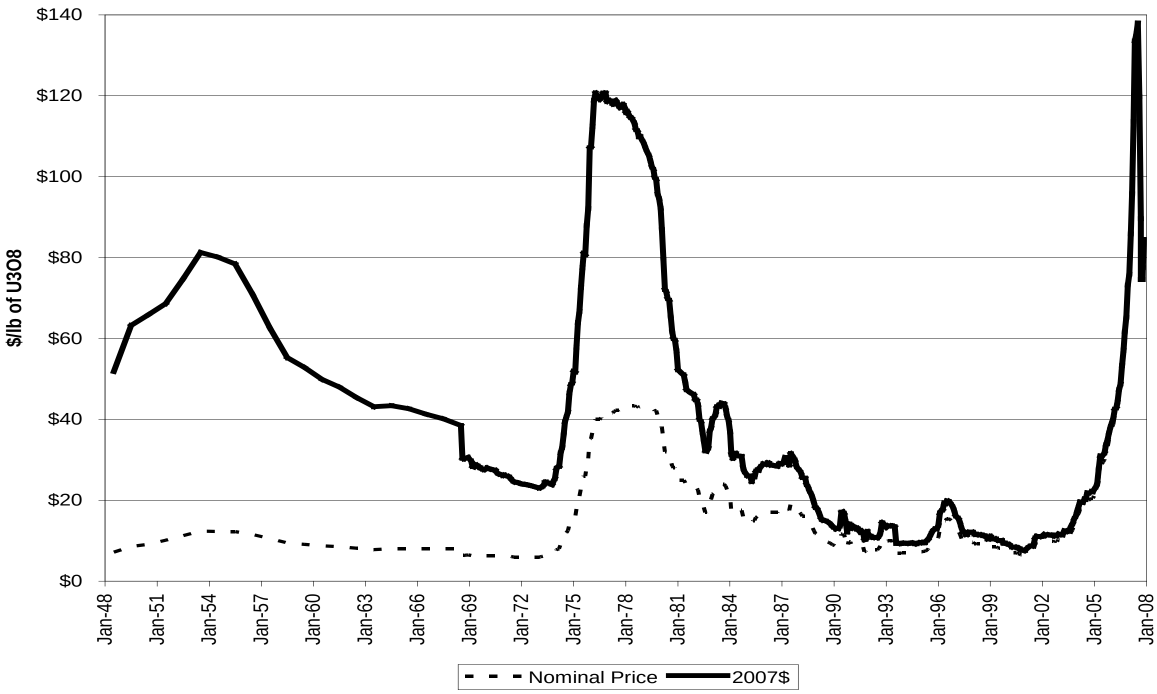

Figure 1: Uranium Prices from 1948 to 2007

purchases and the price declined.[19]

The relatively low uranium prices in the period up to the mid-1970s led some to predict continued low and stable uranium prices in the future, a situation that may have some similarity with the situation today. In this low-price period, Westinghouse entered into nuclear power plant contracts that included fixed-price nuclear fuel supplies and was caught in a significant commercial bind that resulted in defaults when uranium market prices increased because Westinghouse had not hedged its fixed-price nuclear fuel contracts with uranium stocks or contracts.[20]

The second price spike was in the 1970s and 1980s, when the first generation of commercial nuclear power plants were placed in operation. Expectations of high growth in nuclear capacity in the 1970s were similar to the current optimistic outlook for the nuclear industry. When the development of the first generation of nuclear plants slowed, both before and after the Three Mile Island incident in 1979 and the Chernobyl accident in 1986, the actual and expected demand for nuclear fuel declined along with uranium prices.[21] The lower prices after 1985 led many uranium producers to cease operations, and by 1990 world uranium production fell below world demand and has remained below demand since then, as shown in Figure 2.[22]

As in the mid-1970s, low prices in the uranium market between 1985 and 2003 have led to expectations that uranium prices will be low and stable in the future. These expectations were upset by the third uranium price spike that began in late 2003. Uranium spot prices moved from below $20/lb in 2004 to an all-time high price (even compared to historical prices adjusted for inflation) of $138/lb in July 2007.

Nuclear industry plant operators and nuclear fuel buyers have referred to this recent uranium price increase as unsustainable, have characterized recent high prices as the result of speculation with little connection to market fundamentals, and have generally predicted a quick return to lower and more stable uranium prices. Uranium spot prices are likely to remain at levels well above 2004 levels as uranium demand continues to grow, even though uranium spot prices had

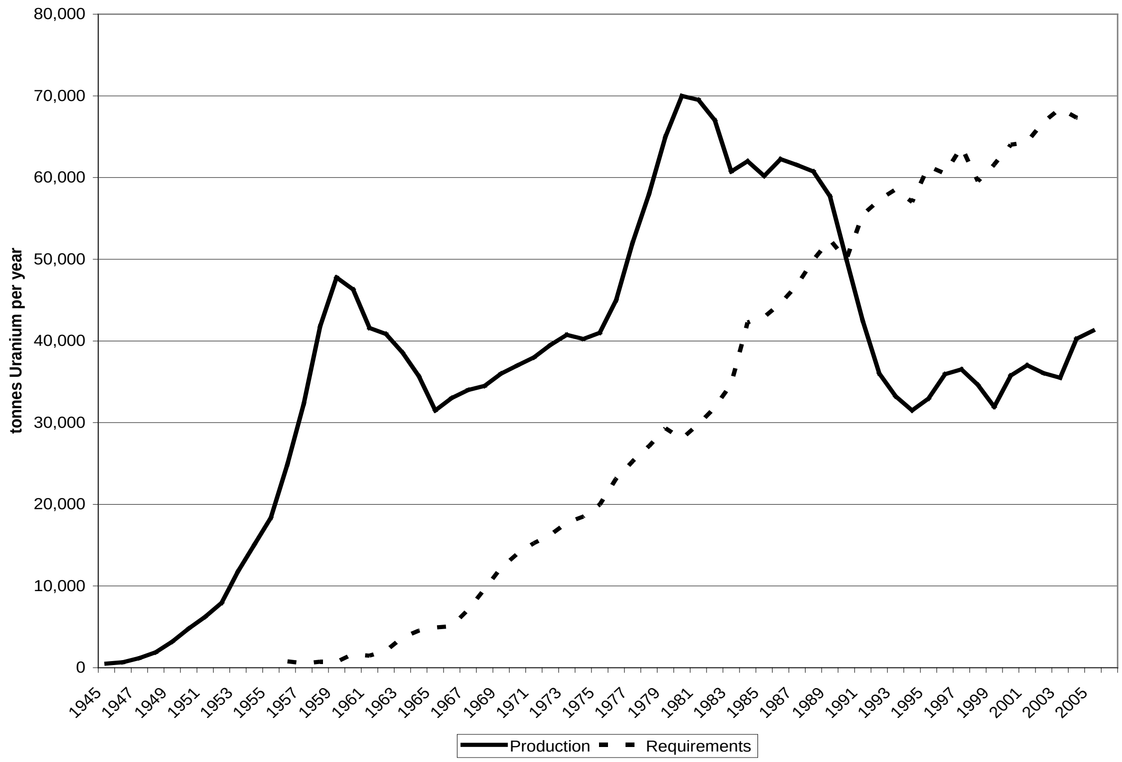

Figure 2: World Uranium Production and Requirements from 1945 to 2005

dropped to $75/lb by the end of September 2007.

Uranium spot price increases do not directly increase nuclear fuel costs, because most uranium is procured through contracts. However, if uranium spot prices remain high, it is likely that uranium contract prices will eventually rise as well. The 2007 uranium spot price spike introduced an element of uncertainty into the outlook for future nuclear fuel costs.

Given the uranium spot price pattern over the past 60 years, significant investment may be delayed until there are sustained uranium prices at or above long-run marginal cost. Investment in uranium exploration and mine development that is starting today will not result in increases in uranium production for 10 years or more.[23]

Cameco planned to bring the massive high-grade Cigar Lake uranium mine online in 2008, with full-scale annual production of more than 10% of total world uranium demand, but a flood at this complex facility[24] in late 2006 delayed the mine's development. While Cigar Lake will eventually be placed into production, the problems at the mine illustrate the difficulty in bringing high-quality mines into full production. Likewise, an early 2007 cyclone flooded the Australian Ranger open-pit mine and may stop production for a year or more as the mine is dewatered and production is restored.

It is likely that long-term uranium prices will be significantly higher than spot prices between 1985 and 2003 as the market supply of uranium increases to meet demand and as the secondary sources that currently supply over 40 percent of world uranium demand are depleted.

Uranium producers require higher uranium prices to justify investment in exploration and new mine development. As the demand for uranium exceeds the production of mines with high-grade ore bodies, new mines will exploit lower-grade uranium ore bodies and will have lower yields and higher production costs. The cost of uranium exploration and mining will also increase as a result of increases in power costs, increases in fuel costs, increases in activities necessary to meet ever-stringent environmental requirements, and general price increases for steel and other construction materials.

Experience with other mined commodities has shown the potential for advances in exploration and extraction technologies that will allow production of lower-grade ore bodies at lower costs. There is some potential that new currently-unknown high-grade uranium ore bodies will be discovered and that new uranium mining techniques will be developed that will lower production costs, but these may not offset the relatively certain increases in the cost of developing and operating uranium mines.

The availability of other nuclear fuel sources such as plutonium-based MOX fuel may put a cap on the market price of uranium, although such price caps are likely to be relatively high.

VI. Enrichment

The other major component of nuclear fuel cost is enrichment.

Commercial uranium enrichment is energy-intensive. Enrichment processes force gaseous UF6 through a semi-porous membrane (diffusion) or spin it at high speed (centrifuge). The end result of the enrichment process is two streams of UF6 - enriched uranium product and enrichment tails. Enriched uranium product has a concentration of 3% to 5% U-235 and is used for nuclear fuel. Enrichment tails are mostly U-238, with only a small amount of U-235 (e.g., 0.25%; known as the tails assay).

The capacity of enrichment plants is measured in terms of 'separative work units' or SWU. A SWU is a complex unit which is a function of the amount of uranium processed and the degree to which it is enriched (i.e., the extent of increase in the concentration of the U-235 isotope relative to the remainder) and the tails assay.[25]

Enrichment and natural uranium are substitutes. For a set of natural uranium prices, enrichment prices and enrichment levels, there is an optimal tails assay that will minimize the total cost of the enriched uranium product. [26]

For a given SWU price, enrichment to a lower tails assay and higher SWU level may be used when uranium prices are high, so that enriched uranium product is produced with less natural uranium feedstock. If uranium prices are low, then enrichment at a higher tails assay and a lower SWU level may be used, so that the enriched uranium product uses more cheap uranium feedstock but less SWU to minimize total cost of enriched uranium. Similarly, for a given uranium price, a change in enrichment price may also lead to changes in the tails assay to minimize the cost of enriched uranium product.

Some enrichment tails may have a relatively high tails assay (e.g., 0.25% or greater) as a result of enrichment during periods when natural uranium feedstock was available at low prices. These high-assay enrichment tails can be put through the enrichment process again to produce enriched uranium product, displacing natural uranium feedstock.[27]

Like the uranium markets, the enrichment market has been heavily influenced by government activity.

In the US, the only enrichment facilities were owned by the US Government until the government facilities were privatized into the US Enrichment Corporation in 1998. USEC has put the Piketon diffusion plant in standby and has consolidated its operations at the Paducah plant. USEC is currently developing the new American Centrifuge Enrichment Plant, but this facility will not be in full operation for years.[28]

Several European enrichment facilities are in operation, with Urenco expanding its centrifuge capacity in the US at the LES MEF facility in New Mexico.[29] The Russian enrichment facilities have remained in government ownership, but have been significantly upgraded and converted to commercial use.[30]

Like the demand for uranium, the demand for enrichment services will grow as a result of continued operation of existing nuclear power plants and the additions of new nuclear plants. A portion of the current enrichment demand is met by the use of blended-down Russian HEU. As the demand for enriched fuel grows and the Russian HEU arrangement ends, there will be a need for more enrichment capacity in the US and Europe.

If long-term prices for natural uranium remain high levels, enrichment at lower tails assays will be used to reduce the amount and cost of natural uranium feedstock and will increase the need for enrichment above the current level, even without any growth in nuclear fuel demand.

Also, the trend toward higher fuel burnup and longer fuel cycles in commercial nuclear power plants by using nuclear fuel at higher enrichment levels will mean an increase in the demand for enrichment services.[31]

Two factors that may mitigate an increase in enrichment demand and prices are the increase in Russian enrichment capacity that may play an expanded role in world enrichment markets and the use of plutonium-based MOX fuel that replaces enriched uranium fuel. Finally, there is the possibility that new high-speed centrifuge technology or new laser enrichment technology[32] will result in enrichment services at lower costs than existing technology.

USEC is in the process of retiring its diffusion enrichment plants and these are expected to be shut down between 2009 and 2012, removing about 8 million SWU/year, followed by the end of the Russian HEU blend-down arrangements in 2013, removing the equivalent of about 6 million SWU/year from the US market.

European and Russian enrichment facilities are expected to increase capacity and the new LES facility will add about 3 million SWU / year to the US market by 2013. Russian enrichment capacity may be offered into the US enrichment market directly, but this is subject to trade restrictions that may not be lifted or that may be lifted with specific caps on the amount of Russian enrichment capacity that can be offered into the US market.

Total world demand for enrichment services is currently about 44 million SWU/year and is expected to grow to about 63 million SWU/year by 2025. Supply of enrichment services is expected to slightly exceed demand until 2009, when existing and planned enrichment capacity is expected to fall below world demand by increasing amounts, leading to a deficit of enrichment capacity of more than 8 million SWU/year in 2025. [33]

Reported prices for enrichment services increased from $85/SWU in December 2000 to $140/SWU in mid-2007. This increase is less dramatic than the recent spike in uranium spot prices, but adds to nuclear fuel cost.

The overall outlook for enrichment is the potential for continued higher prices and the potential for shortfalls in supplies after 2009.

VII. Conclusions

The demand for nuclear fuel is expected to grow significantly over the next 10 to 20 years. The uranium and enrichment industries, consisting of commercial entities, must invest considerable amounts of capital in order to increase supply and face a 10 to 20 years process to develop new producing uranium mines and new enrichment facilities.

While there will be enough nuclear fuel to meet world demand, there is uncertainty about the price and timing of uranium and enrichment services as these markets make the transition to supply and demand equilibrium without secondary supplies. During this transition period, the prices of uranium and enrichment services are likely to be high and volatile. Importantly, the impact of events such as the Ranger mine flooding will become increasingly high as the nuclear fuel markets tighten. The use of force majeure provisions in the Ranger mine flood shows that even long-term contracts may not ensure supplies or prices for nuclear fuel.

By the time the first new nuclear power plants in the US become operational in about 2016, the nuclear fuel market will still reflect high and volatile transition period prices. Economic analyses of new nuclear power plants should reflect the uncertainty of nuclear fuel prices and the potential for high and volatile prices during this 20-year transition period. ■

Endnotes:

1. Most power reactors use uranium fuel, although some light water reactors can and do use mixed-oxide plutonium fuel to replace or supplement uranium fuel.

2. If enrichment is not required (e.g., for fuel to be used in the original Canadian CANDU and early British gas-cooled MAGNOX reactors), then the refined yellowcake is converted, without enrichment, to uranium dioxide (UO2) that is used to fabricate fuel.

3. A poison is a material that absorbs neutrons that would otherwise cause fission. A burnable poison is one that has its effectiveness as a neutron absorber diminished by exposure to neutrons, so that it absorbs fewer neutrons over time spent in an operating reactor core and allows higher initial fuel loads.

4. Fission products are the atoms that remain when a U-235 atom breaks apart in the fission process. Some of these fission products hinder the fission process for the remaining U-235. During power operation, some of the U-238 in the reactor core is turned into plutonium that also undergoes fission, providing heat energy and producing fission products.

5 The 'back end' of the nuclear fuel cycle consists of the disposition of the nuclear fuel assemblies after they are removed from the power reactor (known as spent or used nuclear fuel). Spent or used fuel assemblies may be stored, perhaps permanently, or they may be reprocessed or recycled. The back end of the nuclear fuel cycle presents complex and difficult policy issues due to the long time frames associated with spent nuclear fuel and the linkage to nuclear weapons proliferation issues.

6. *Uranium 2005: Resources, Production and Demand*; a Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, OECD NEA No. 6098; 2006; Table 20.

7. *Id.*, Table 21.

8. *US Electricity Production Costs 1995-2006*; Nuclear Energy Institute, updated June 2007.

9. Even with a nuclear fuel cost of $10/MWh or more, nuclear electricity might regain a production cost advantage over coal generation as a result of carbon tax policies.

10. Most utilities have adopted a dispatch regime that uses nuclear plant output whenever a nuclear plant is operational. This practice has been reflected in electricity markets rules, where nuclear plants are typically allowed to choose to operate as "price-takers" that are always dispatched if available, but that do not set the market price.

11. As an example, a $5/MWh increase in nuclear fuel costs would mean over $50 million a year in higher costs and lower profits for a single large power nuclear power plant.

12. If spent fuel reprocessing, use of plutonium MOX fuel, and fast breeder reactors are assumed to be in use, this period is significantly longer.

13. *Uranium 2005, supra* note 6.

14. The NEA production cost levels are US$40/kgU ($18.2/lb); US$80/kgU ($36.4/lb); and US$130/kgU ($59.1/lb). These costs include the direct costs of mining, transporting and processing uranium ore, the associated costs of environmental and waste management, financing costs and the general costs associated with running the operation. Sunk costs (including exploration and mine development costs) are not included. These NEA production cost levels may be lower than prices that would be required to develop new mines to produce the RAR.

15. *Uranium 2005, supra* note 6.

16. Haruo Maeda; *WNA Market Report*; World Nuclear Association Annual Symposium; 2005.

17. *Economic Assessment of Used Nuclear Fuel Management in the United States*; July 2006; Prepared by the Boston Consulting Group for AREVA; page 21.

18. *Amended Record of Decision, Surplus Plutonium Disposition Program*; US Department of Energy; Federal Register: April 19, 2002 (Volume 67, Number 76); pp. 19432 to 19435.

19. *Uranium Price Formation*, Electric Power Research Institute Report EA-498, October 1977, Prepared by Charles River Associates.

20. Paul L. Joskow, *Commercial Impossibility, the Uranium Market and the Westinghouse Case*, The Journal of Legal Studies, Vol. 6, No. 1 (Jan., 1977), pp. 119-176.

21. Thomas L. Neff, THE INTERNATIONAL URANIUM MARKET Ballinger Publishing Company, Cambridge, Massachusetts, 1984

22. *Forty Years of Uranium Resources, Production and Demand in Perspective, "The Red Book Retrospective"*; OECD NEA No. 6096, 2006, Figure 7.5 on page 95.

23. *Id.*, at 141 - 148.

24. The mining process used at Cigar Lake involved the circulation of freezing brine underground for months to freeze and stabilize the earth before working mine shafts could be completed.

25. For example, 3.8 SWU is required to enrich natural uranium feedstock into one kilogram of enriched uranium product at 3% U-235 and a tails assay of 0.25%. This increases to 5.0 SWU if the tails assay is reduced to 0.15%, but requires less natural uranium feedstock.

26. Thomas L. Neff, *Enrichment Tails Assay and Uranium Supply: A Dynamic Relationship*, MIT

27. Because enrichment tails are usually in the form of UF6, re-enrichment of tails avoids the costs associated with mining, processing, conversion, and transportation.

28. *Environmental Report for the American Centrifuge Plant, Revision 7*; US Enrichment Corporation American Centrifuge Plant license application, NRC Docket No. 70-7004

29. NEF Environmental Report, December 2003; Louisiana Enrichment Services, L. P., National Enrichment Facility license application, NRC Docket No. 70-3103

30. Oleg Bukharin, *Understanding Russia's Uranium Enrichment Complex*, SCIENCE & GLOBAL SECURITY, Volume 12, pp. 193-218; 2004

31. *Very High Burn-ups in Light Water Reactors*; OECD NEA No. 6224, 2006.

32. An Australian enrichment approach called SILEX (Separation of Isotopes by Laser EXcitation) is under commercial development by General Electric. Another laser enrichment approach called AVLIS (Atomic Vapor Laser Isotope Separation) uses lasers tuned to frequencies that ionize only U-235 atoms that are attracted to a negatively-charged plate and collected.

33. Thomas B. Meade and Michael H. Schwartz, *The Market for Uranium Enrichment Services*; Energy Resources International, Inc.; Nuclear Energy Review 2007; Touch Briefings 2007; pp. 23-24.