A Review of Uranium Economics

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ABSTRACT
Recent increase in demand of power for commercial use, the challenges facing fossil-fuel and the prospective of cheap nuclear power motivate different countries to plan use of nuclear power. This paper reviews many aspects of Uranium economics, which includes advantages and disadvantages of nuclear power, comparisons of other sources of power, nuclear power production and requirements, uranium market, uranium pricing, spot price and long term price indicators, and the cost of building nuclear power facility.

1. INTRODUCTION
Increasing demand of commercial power, especially electricity, and the problems of limited oil reserve, has paved the road for searching for other sources of power generation. In addition to oil, different countries are looking for different sources of power, which include coal, solar, wind, natural gas, biofuel, and nuclear power sources. In recent years many countries are planning to use the nuclear power for peaceful commercial use. The goal of this paper is to cover the main aspects of nuclear power option which is the economics.

The use of nuclear power is controversial because of the problems of storing radioactive waste for indefinite periods, the potential for possibly severe radioactive contamination by accident or sabotage, and the possibility that its use in some countries could lead to the proliferation of nuclear weapons. Proponents believe that these risks are small and can be further reduced by the technology in the new reactors. They further claim that the safety record is already good when compared to other fossil-fuel plants, that it releases much less radioactive waste than coal power, and that nuclear power is a sustainable energy source. Critics, including most major environmental groups, believe nuclear power is an uneconomic, unsound and potentially dangerous energy source, especially compared to renewable energy, and dispute whether the costs and risks can be reduced through new technology.

From economical point of view the cost is the main issue. Many studies showed that the cost of nuclear power in less than the cost of other sources of power generation. Table I below shows such comparison ([1]). However, opponents of nuclear power argue that any of the economical and environmental benefits are outweighed by safety compromises and by the costs related to construction and operation of nuclear power plants, including costs for spent-fuel disposal and plant retirement. Proponents of nuclear power respond that nuclear energy is the only power source which explicitly factors the estimated costs for waste containment and plant decommissioning into its overall cost, and that the quoted cost of fossil fuel plants is deceptively low for this reason. The cost of some renewables would be increased too if they included necessary back-up due to their intermittent nature.

2. OVERVIEW OF COMMERCIAL NUCLEAR POWER
It became clear that electricity demand, which had been experiencing annual growth rates, was suffering from the economic impact of the oil supply problems. Consequently, the power generation using nuclear fuel became an option for many countries. Nuclear plant orders became at risk for lack of anticipated future demand for electricity. The world’s uranium production increased from about 105 million pounds U$_3$O$_8$ in 1973 up to almost 175 million pounds in the 1980-81, the historical peak. Actual world consumption for the years 1980-81 averaged only 55 million pounds U$_3$O$_8$ per year. This high production, relative to consumption, was sustained through about 1988, before starting to decline thereafter. There were several reasons that production did not decline in the early to mid-1980s, in spite of the price decline. For one, the long-term, fixed-commitment enrichment contracts fostered the development of long-term uranium supply contracts, whose prevalent pricing mechanisms were base-prices with escalation, from bases of $40 or so for contracts signed in the mid- to late-1970s; and market-related prices with price floors typically around $35 per pound U$_3$O$_8$ for contracts signed in the mid- to late-1970s. Thus, producers with long-term contracts were protected from drops in the spot price. The second reason for sustained production was the discovery and development of a new class of “super deposits” of large size and low production costs in Australia and Canada. Thus, while production was declining from older low-grade deposits, this lost production was being replaced by new high-grade deposits. Throughout most of the 1984-1988, the Exchange Value was in the $15-17 per pound U$_3$O$_8$ range. However, a sustained decline continued, due to pressure from the huge overhang of excess commercial inventories and the entry of supplies from the Soviet Union into the West.
Cost Comparison Summary

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<td>6.5 - 8.5?</td>
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Table I: Cost comparisons of different sources of power

The uranium trading companies bought and sold uranium for their own account, typically purchasing large quantities from utilities with large excess inventories or from the Soviet Union (and, later, FSU), then reselling in smaller lots to match market demand. The uranium spot price dropped below $10 per pound U₃O₈ in May 1989—reaching the $7-8 range from late 1991 through mid-1992. Late 1991 saw the beginning of the era of protection of the market, with the filing of a dumping complaint by some US producers against uranium from the Soviet Union. Shortly after that filing, the Soviet Union was dissolved, and the dumping investigation was continued against the six FSU countries that were determined to have produced uranium in the past. In early-to mid-1992, the US Department of Commerce (DOC) found preliminary justification in the complaint and ordered an interim dumping duty of 148% on uranium from these countries. The FSU countries were thus faced with the prospect of intolerable dumping duties, and the US government was faced with the dilemma of trying to reward the FSU countries for “throwing off the yoke of communism” in the face of impending trade restrictions on one of the few products these countries had to export. The compromise was the implementation of so-called suspension agreements between the DOC and the FSU countries, under which the FSU countries individually agreed to limit their exports to the USA. The suspension agreements were put into place in October 1992, and the Euratom Supply Agency in Western Europe followed suit with its own brand of trade restrictions against FSU uranium. A market bifurcation resulted, with FSU uranium selling at a $2-3 discount from non-FSU uranium. This discount range generally persisted from late 1992 through mid-2001. Import restrictions have been discontinued in the USA against all but Russian uranium, whereas Euratom continues its overall guidelines restricting use of FSU uranium in general ([2] &[3]).

3. WORLD URANIUM PRODUCTION AND REQUIREMENT

Uranium consists primarily of two “isotopes” with the same chemical characteristics. Both isotopes have 92 protons in their nuclei, but the lighter isotope, U-235, has 143 neutrons, i.e. atomic weight of 235, and the heavier isotope, U-238, has 146 neutrons. U-235 comprises only 0.7% of natural uranium, but it is the only isotope that can actually undergo fission and produce energy; and U-238 comprises the remaining 99.3% of natural uranium. In order to be useful as fuel in the most nuclear power technologies, the percentage of U-235 must be increased to the level of 2-5% U-235, a process called “enrichment.” Enrichment is a technically difficult process, the essence of which is highly secret because it is the same process used to produce some nuclear weapons material. Nuclear weapons made from uranium of approximately 90% U-235.

When the Western world’s nuclear power industry was starting its commercialization, the only supplier of uranium in the USA was the US Atomic Energy Commission (AEC). Under US legislation passed in 1964, private ownership of uranium was allowed starting in 1968. The same legislation authorized the AEC to provide “toll enriching services” for uranium, under nondiscriminatory terms, on the basis of the AEC’s recovery of its costs of providing such services. This part of the legislation was a clear mandate to the US government to involve itself in the commercial nuclear fuel industry only by providing enrichment services, and not the other segments of the fuel industry. This led to markets for each processing stage for nuclear fuel—markets that persist to this day. A typical utility buyer will contract separately for natural uranium concentrates “U₃O₈” (yellowcake), services for processing U₃O₈ into uranium hexafluoride (UF₆) conversion, services “SWU” for enriching uranium in its U₂35 content, and services for fabricating the Enriched Uranium Product (EUP) into finished fuel assemblies for loading into the
nuclear power plant. Figure 1 and tables II & III show the world uranium production and requirement Data for the period 1999-2007 ([2] & [3]).

The company fabricating the fuel assemblies does not normally use the EUP delivered by that customer to manufacture the customer’s actual fuel assemblies. In actual practice, the utility customer is asked by the fabricator to deliver EUP of different characteristics (quantity and U-235 enrichment) than that used for that customer’s fuel assemblies. In fact, the customer usually orders EUP matching a future fabrication customer’s needs. In each such case, the customer delivers EUP of the same enrichment services (SWU) content, but different natural uranium equivalent.

4. URANIUM MARKET

Uranium is bought and sold in two distinct markets: spot and long-term ([4]). The spot uranium market is that in which a single delivery is made within one year of contract execution. The long-term, or forward, market is one in which a series of deliveries is made over a period greater than one year. Although there is no formal “market” for uranium and SWU, in which standardized sales terms and quantities exist, several organizations publish prices for activity in these markets. The longest running of the uranium price series is the NUEXCO Exchange Value, currently published by TradeTech ([3]) and in publication since the beginning of the commercial market for uranium in August of 1968. The Exchange Value is a measure of the uranium price on the spot market, but is also used in the vast majority of long-term contracts with “market-related” delivery prices. In addition, the Exchange Value has been published as two series; one for the “Restricted Market”, i.e., with import restrictions on uranium from the countries of the former Soviet Union, or later FSU, and one for the “Unrestricted Market”, i.e., for regions with no import restrictions.

The market reacted to these restrictions in two stages. First, the price for non-FSU uranium in the restricted markets rose to over $10 per pound U₃O₈, staying in the $9-10 range until the early 1995 period. By February 1995, the depletion of commercial inventories available to the restricted markets and the bankruptcy of NUEXCO helped the price rise from $10.40 in February 1995 to a peak of $16.50 in the May-July 1996 period. This price run-up was short-lived, as pent-up production responded and the FSU suspension agreements had been modified earlier in 1994 to effectively loosen the terms of the import restrictions. In fact, the Russian suspension agreement was modified to allow “matched sales” with equal parts of US-produced uranium and Russian imports, under terms that effectively subsidized the US producers. The “restricted” spot price dropped below $12 per pound U₃O₈ in May 1997. The spot market has seen some upward price excursions in late 1997 and early 1999, but was generally on a downward incline since late 1996, especially during the year 2000.

After a rise to a plateau of about $10 per pound U₃O₈ in early 2001, the spot price began rising in April 2003 as a shift from a buyers’ market to a sellers’ market was initiated. This trend continued into 2004 with gradual increases in the spot uranium price and gained even more momentum the following year. The year 2005 was marking the most dramatic rise in the spot uranium price since 1975. The spot price at the beginning of 2005 was $21.20 per pound U₃O₈; however, by December 31, 2005, the spot price had risen by more than $15, to $36.50 per pound U₃O₈. A driving force behind this increase was the entry into the market of a new type of buyer—the investor/speculator. Total sales volume for 2005 was slightly less than 30 million pounds U₃O₈ equivalent, and investors accounted for more than 36% of all spot uranium purchases.

The spot uranium price rose to $40 per pound U₃O₈ on March 20, 2006—the first time since January 1980 that the uranium market has seen a spot price reach this level. By the end of August 2006, the spot price had climbed to $52 per pound U₃O₈, marking a record level in the history of uranium price reporting that began in 1968 by TradeTech predecessor NUEXCO. Just two months later, the price broke through another barrier by reaching $60.25 per pound U₃O₈ on October 31, 2006. The spot price jumped 7% after Cameco Corp. announced a flooding incident at its Cigar Lake uranium project in Canada and warned of a mine production delay of more than a year. At the end of 2006, the spot price had settled at $72 per pound U₃O₈. The year 2007 has witnessed more increases in TradeTech’s ([3]) spot uranium price as investor interest in the market continues to surge and near-term uranium supplies remain thin. On April 6, 2007, TradeTech’s uranium spot price jumped $18 to $113.00 per pound U₃O₈, following the results of the sealed-bid auction of 100 thousand pounds U₃O₈ by a US producer. This is the largest single increase since uranium prices were first reported by NUEXCO in 1968, and marks a 57 percent increase in the spot uranium price since the beginning of the year. On May 4, 2007, TradeTech’s uranium spot price soared to $120 per pound U₃O₈.

A Futures contracts, launched on May 7, 2007, by the New York Mercantile Exchange, Inc., involves financially settled contracts that are separate from the physical uranium market and sets the stage for a new set of players in the market. The price run-up continued and peaked at an all-time high of $138.00 per pound U₃O₈ on June 1, 2007, after another auction with intense biddings, where it stayed for four weeks. On June 30, 2007, the spot price began to drop. After 23 consecutive months of tight supply, rising spot prices and intense bidding for material, buying interest waned considerably and the market witnessed increasing interest on the part of sellers to move material. On August 10, 2007, the uranium spot price plunged $15 to $120.00 per pound U₃O₈, the largest single drop recorded in the spot price since the uranium price was first published.
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<td>104,451</td>
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Table II: World Uranium Production Data (thousand pounds U₃O₈)
A number of factors contributed to the price decrease, the most influential of which was the introduction of supply from a variety of sources. The reasons for the influx of material vary from seller to seller, but have primarily been driven by the individual sellers’ desire or need to generate cash. Another factor that contributed to the downturn in prices is the sharp decrease in demand that has occurred over the past several months. Utility buying has fallen off sharply in recent months primarily due to the high prices, and thus, budgetary and financial burden associated with acquiring material. Although the buying interest remains weak, some buyers are watching the drop in prices closely with a view toward re-entering the market. The price decline, however, lasted nearly four months, and it began to increase on October 12, 2007 when it rose $2 to $80.00 per pound U₃O₈. The price increase began gradually, but by month-end the price gained momentum as news of production shortfalls from a variety of producers made its way into the market. The news that Uranium would miss its production targets in 2007 and 2008 by a significant margin, followed by the official announcement from Cameco that the production startup date for Cigar Lake is now expected to be 2011, at the earliest, prompted sellers to withdraw from the market. On December 31, 2007, the Exchange Value settled at $89.00 per pound U₃O₈.

### Table III. World Uranium Requirement Data ¹(Thousand pounds U₃O₈)

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<td>35,000</td>
<td>10,700</td>
<td>171,100</td>
</tr>
<tr>
<td>2007</td>
<td>49,500</td>
<td>53,600</td>
<td>20,800</td>
<td>35,300</td>
<td>9,100</td>
<td>168,300</td>
</tr>
</tbody>
</table>

1. Calculated by TradeTech based on actual completion dates and operating performance, and TradeTech’s estimate of enriching tails assay. 2. European Union (EU) includes: Belgium, Finland, France, Germany, Italy, the Netherlands, Spain, Sweden, and the UK. 3. CIS/Non-European Union Armenia, Bulgaria, Czech Republic, Hungary, Kazakhstan, Lithuania, Romania, Russia, Slovak Republic, Slovenia, Switzerland, Turkey, and Ukraine. 4. Asian Pacific includes: Japan, China, South Korea, and Taiwan. 5. Other includes: Argentina, Brazil, Canada, India, Mexico, Pakistan, and South Africa.

In order to mine new uranium, prices paid to producers must fully cover production cost plus some return on investment. As massive inventories began to be liquidated in the 1980s and uranium prices steadily declined, the producers’ need to receive a positive return on investment was often at odds with the needs of utilities. These diverging requirements led to a variety of increasingly complex pricing mechanisms in long-term contracts. However, no generally accepted long-term price indicator existed until 1996, when TradeTech began publishing its monthly Long-Term Price Indicators for U₃O₈, conversion and SWU market segments. The indicators, which were introduced in March 1996, are TradeTech’s judgment of the base price at which transactions for long-term delivery of that product or service could be concluded as of the last day of the month, for transactions in which the price at the time of delivery would be an escalation of the base price from a previous point in time.

In the early years of the commercial uranium market the commercial nuclear power industry was just in its infancy. Consequently, uranium prices were at their all-time historical low. Several factors appeared in the mid-1970s to change this situation. First, nuclear power became more widely accepted economically as a source of electricity by the world’s utility industry, and the years 1973-1976 witnessed massive orders of nuclear power capacity. Second, there was a strategic push by governments to energy sources other than oil in response to 1973 war results. Third, the world’s only supplier of enrichment services (US) first closed its order books because of its perceived enrichment capacity shortage, and then reopened new contracting by shifting from requirements-based contracts to contracts with 10-year-forward firm commitments, thus fixing uranium demand that far into the future. Finally, there was the alleged formation of a cartel by non-US producers, partially in response to US import quotas on foreign uranium, followed by the abrogation of a large number of contracts by the Westinghouse Corp., which had sold uranium short as part of package deals for nuclear power plants. The price consequently rose rapidly from $7 per pound U₃O₈ at the end of 1973, to $14 in October 1974, to $21 in May 1975, to

### 5. URANIUM PRICING

Most uranium sold on the spot market comes from excess inventory and uncommitted mine production. As such, prices in this market are normally assumed to be unrelated to production costs. Sellers price material based on a perceived balance of supply and demand at the time an offer is made. Several spot price indicators are published that are generally accepted by the industry as accurate reflections of current spot price levels. Historically, a large portion of long-term supply, supply sold in the forward market, has come from primary production, and it follows that prices in this market have commonly been assumed to reflect production costs.
$40 in April 1976, before peaking at $43.40 in May-July 1978 ([3]).

5.1 Book Transfer of Uranium

Natural uranium (U\textsubscript{3}O\textsubscript{8} and UF\textsubscript{6}) is nearly always sold by “book transfer” at a processing facility, after being delivered to the facility, and sampled and weighed by the processor. Although uranium is physically delivered to the facility under the ownership of a given entity, the delivered uranium is most often processed not in identifiable batches, but rather in a continuous processing stream. The processor typically has the right to use the delivered material as “working inventory”. Thus, ownership of the uranium is actually a book entry in the processor’s inventory records. It is very rare for there to be a physical lot that is identified with a given owner. A “delivery” under a sales contract is then made by the seller giving notice to the facility owner that the uranium ownership is to be transferred from the seller’s storage account to the buyer’s storage account at the facility. Both buyer and seller must have previously established storage accounts at the facility. Book transfer has several advantages over physical delivery:

- Delivery can be at any date deemed by the parties, since the material doesn’t have to be physically transported and, thus, subject to timing uncertainties;
- Any lot size convenient to the buyer and seller can be transferred, rather than being constrained by the physical sizes of containers;
- The delivery is “certified” by a third party, the facility owner, since the material must exist in the seller’s account to be transferred and the facility owner will then notify both parties that such ownership transfer has been made; and
- The transaction is kept confidential among the buyer, seller, and facility owner, since there are no reporting requirements.

The sale of processing services in the spot market can be made by parties that have no processing facilities but do have title to processed material, in a slightly more complicated way than a straight sale of uranium products. For example, a holder of natural (i.e., un-enriched) UF\textsubscript{6} inventory can sell UF\textsubscript{6} conversion services by exchanging some of its natural UF\textsubscript{6} for the same amount of U\textsubscript{3}O\textsubscript{8} that would have been delivered under a processing contract, and then being paid for the UF\textsubscript{6} conversion services contained in that exchanged UF\textsubscript{6}. In such a case, the buyer and seller typically notify the owner of the facility at which the respective lots are being stored to carry out a book transfer of the seller’s UF\textsubscript{6} to the buyer’s account and the buyer’s U\textsubscript{3}O\textsubscript{8} to the seller’s account. These transfers can even be made at separate facilities, so that the buyer may deliver its U\textsubscript{3}O\textsubscript{8} at one facility and receive its UF\textsubscript{6} at another facility, thereby avoiding the need to incur a transportation cost, See figure 2.

5.2 Transportation Cost

Since most processing contracts are set up with the buyer’s delivery of U\textsubscript{3}O\textsubscript{8} at a conversion facility and delivery taken of UF\textsubscript{6} at an enrichment facility, the converter pays the transportation charge from his facility to the enrichment plant. This is a result of the fact that it has generally been a buyers’ market, so that the seller is expected to incur the transportation cost to the buyer’s designated facility. However, there is currently a great deal of uncertainty about the cost impact of future regulations for shipping UF\textsubscript{6} from North America to Europe, and this has caused recent offerers of conversion services or natural UF\textsubscript{6} to require their new buyers to absorb the increased cost of this transportation.

6. PRICE INDICATORS

Uranium price indicators are developed by a small number of private business organizations, like TradeTech and The Ux Consulting Company (UxC) ([3] & [5]), that independently monitor uranium market activities, including offers, bids, and transactions. Such price indicators are owned by and proprietary to the business that has developed them.

6.1 Ux Price Indicators

The Ux U\textsubscript{3}O\textsubscript{8} price is one of only two weekly uranium price indicators that are accepted by the uranium industry, as witnessed by their inclusion in most “market price” sales contracts, that is sales contracts with pricing provisions that call for the future uranium delivery price to be equal to the market price at or around the time of delivery. The Ux U\textsubscript{3}O\textsubscript{8} price is the longest-running weekly uranium price series, dating back two decades. In addition to being used by the industry in sales contracts, Ux price indicators have been referenced by the U.S. Government in the determination of price-tied quotas and for determination of prices in the highly enriched uranium (HEU) deal between the U.S. and Russian Governments. Ux price indicators are also referenced in The Wall Street Journal ([6]), and other major media publications when they discuss uranium price developments. It is important to note that UxC remains an independent and unbiased entity in the acquisition, analysis, development, and reporting of uranium pricing data. Compliance with this policy has gained the long-term trust of the industry that UxC’s price indicators are accurate and reflect true competitive market conditions. The “spot” market in uranium has traditionally involved contracts calling for delivery as far out as 12 months, although more recently deliveries take place in the forward two to three month period. UxC not only covers the spot uranium market, but also the market
for long-term contracts, as well as the spot and term markets for conversion and enrichment. Figure 3 shows the most recent UxC $U_xO_x$ price indicator.

![Figure 3: Ux U3O8 Price indicator](image_url)

Important insights can be gained by examining the trends in different markets, as well as the changing contracting and procurement policies of the industry. Thus, it is important to know more than just a single price to understand what’s happening in the uranium market, as well as other nuclear fuel markets. For deliveries under long-term uranium contracts, there are two main pricing mechanisms and other three additional pricing mechanisms:

- **Specified Pricing**, in which the price is either a fixed price or a base price plus adjustment for inflation to the date of delivery. The adjustment mechanism is usually either a combination of published indexes, or a fixed annual percentage rate. This mechanism was used almost exclusively during the nuclear industry’s infancy. It was first typically used in sales of steam turbines and electrical equipment to utilities, and was later adapted to the sale of nuclear fuel.

- **Market-Related Pricing**, in which the price is based on the uranium spot market price at or near the time of delivery, and/or some other published market index, such as the average US import price. In most instances, the price is the market price less a discount or plus a premium. The discounts are usually fixed, but in some cases are variable, increasing as the market price increases. Market-related price mechanisms frequently include a floor price below which the contract price may not fall. The floor, which protects the seller, is usually either a base adjusted for inflation, a fixed price, or a production cost-related mechanism. In some cases, the floor used has been a government-specified floor, which is the official floor price of the country that has jurisdiction over the producers’ production and marketing operations. Market-related price mechanisms also frequently include a ceiling price above which the contract price may not rise. The ceiling, which protects the buyer, is usually a base adjusted for inflation or a fixed price.

Although dominant throughout history on a worldwide basis, specified and market-related price mechanisms are not the only types utilized. There exist three additional broad categories of price mechanisms, including “negotiated,” “hybrid,” and “cost-related” pricing.

- **Negotiated price contracts** are defined as those in which prices are to be agreed to periodically (usually annually) by the buyer and seller, and may include the use of an expert or another form of arbitration in the event the parties are unable to agree.

- **Hybrid pricing** is where a market index, such as the spot price, is averaged with either a base-escalated, fixed, or cost-related price. Hybrid pricing frequently involves the use of complex formulae.

- **Cost-related pricing** is where the price is tied to the cost of production from the uranium mine. Usually it is cost plus some margin for profit. Cost-related price mechanisms, however, have been rarely used since the early sellers’ market period.

### 6.2 TradeTech’s Long-Term Price Indicators

In recognition of the importance of the long-term base prices in the nuclear fuel markets, TradeTech began to publish its Long-Term Price Indicators in March 1996. These price indicators are based on TradeTech’s judgment of the base price at which transactions for long-term delivery of that product or service could be concluded as of the last day of the month, for transactions in which the price at the time of delivery would be an escalation of the base price from a previous point in time. The $UF_6$ conversion market is most frequently characterized by contract prices of the specified type, usually a base price escalated up to the date of delivery.

For the long-term enrichment market, through about 1993 the “benchmark” pricing mechanism was the published price of the US government entity (AEC/ERDA/DOE) providing enrichment to the industry. In fact, the early Soviet contracts with Western European countries were typically priced at a discount from the published AEC/ERDA/DOE prices. For the European enrichers, contracts have nearly always been base-escalated pricing, with prices and indexes, denominated in the enricher’s local currency for domestic customers or in US dollars outside the enricher’s home region. Attempts by some US utilities to obtain enrichment contracts with market price-related terms have been unsuccessful. However, a new feature of some enrichment contracts is that utility buyers furnish the electric power required to produce some portion or all of their SWU purchased under the contract. The initial European contracts along these lines were the 1995 renewals of contracts between Eurodif and two of its equity holders. In the USA, Ameren Corp. (formerly Union Electric Company of St. Louis) is believed to be the first to sign such a contract with USEC.

This uranium price series history is shown in figures 4-12 below ([3]). TradeTech’s Long-Term Price Indicators determined as of the last day of the month indicated.
7. COST CALCULATIONS OF NUCLEAR POWER PLANT

To accurately compare the cost of nuclear against other energy sources, one must include the following costs:

1. **Fuel costs**
   Costs associated with the fuel used in the production of energy. For a nuclear plant, these tend to be lower even though the following steps occur in the production of the fuel assemblies used in the reactor:
   1. mining of the uranium ore,
   2. conversion to $\text{U}_3\text{O}_8$ (uranium oxide - yellowcake form),
   3. conversion to uranium hexafluoride,
   4. enrichment from 0.7% $\text{U}-235$ to 2-5% $\text{U}-235$,
   5. conversion to uranium dioxide ($\text{UO}_2$) pellets,
   6. loading of the pellets into rods, then into fuel assemblies.

Transportation costs are high for coal because of the amount of material needed to generate the same energy as the nuclear fuel.

2. **Capital costs**
   Generally, a nuclear power plant is significantly more expensive to build than an equivalent coal-fuelled or gas-fuelled plant. Coal is significantly more expensive than nuclear fuel, and natural gas significantly more expensive than coal — thus, capital costs aside, natural gas-generated power is the most expensive. However servicing the capital costs for a nuclear power dominate the costs of nuclear-generated electricity, contributing about 70% of costs (assuming a 10% discount rate). Costs associated with initial construction of the plant and the modifications are embedded costs. For a nuclear plant these may be higher than for other energy forms because the buildings used for containment or for safety-related equipment must meet higher standards than the traditional structures. Also, safety-related systems are redundant. Such considerations are not important in other energy forms. On the other hand, coal plants are required to include scrubbers to remove airborne pollutants as sulfur dioxide, nitrous oxides, and particulates. However, these costs are influenced by factors as:
   1. Capital costs for plants finished in the 80's were higher due to inflation. Following the oil embargoes in 1973 and 1979, there was considerable emphasis on energy conservation. Also, energy costs rose which had a significant impact on inflation. Because of the drop in expected energy demand, utilities delayed plants under construction, many of which were nuclear and had long lead times for completion. The debt for the delayed plant still incurred interest charges in times when rates exceeded 15%. Short term interest rates in the 80-81 time frame was 20%. As with the federal government debt, that total interest kept increasing so that when the plant went on-line, the total cost of the plant was higher than if the plant had been completed on time. Another related factor was that the delays resulted in higher labor costs - the plants were completed when wages had risen because of inflation. Also, following the Three Mile Island event in 1979, the Nuclear Regulatory Commission (NRC) mandated a number of plant design changes for plants coming on line.
   2. Major equipment replacements. During the 1980's, many older BWRs replaced the recirculation system piping due to corrosion cracking. Some PWRs have had to replace steam generators. Eventually it is expected that most, if not all, PWRs will have to replace steam generators prior to the end of their NRC operating license. In some cases, plants have upgraded turbine generator units to improve power output.

3. **Operation and Maintenance costs**
   The day to day costs associated with operating the nuclear power plant. This includes the costs of:
   1. labor and overheads (e.g. medical and pension benefits),
   2. expendable materials,
3. NRC (e.g. license changes, on-site and regional inspectors, and headquarters staff) and state (e.g. health department, emergency planning) fees,

4. Local property taxes (varies from state to state).

Labor costs in a nuclear plant include those for operators, maintenance personnel (electrical, mechanical, instrument and controls), health physics technicians, engineering personnel (mechanical, electrical, nuclear, chemical, radiological, computer). Materials costs include replacement parts, computer parts, expendable office and other supplies. In general, coal and nuclear plants have the same types of operating costs (operations and maintenance plus fuel costs). However, nuclear and coal differ in the relative size of those costs. Nuclear has lower fuel costs but higher operating and maintenance costs.

4. Waste-Related Costs

The costs associated with the byproduct waste. For a coal plant this is ash. For a nuclear plant, these costs include the surcharge levied by the Department of Energy for ultimate storage of the high level waste. The DOE charge is a flat fee based on energy use.

5. Decommissioning Costs

The costs associated with restoration of the plant site back to "greenfield" status. Usually restoration would occur over a long period of time, e.g. 20 years. Parts of the plant could be used for energy generation by other sources.

6. Loan interests

This is the cost associated with parties that use loans to develop their nuclear facilities.

8. ILLUSTRATIVE COST COMPARISONS

Table IV below compares nuclear versus coal specific item costs for similar age and size plants on a $ per Megawatt-hour (10 $/Mw-hr = 1 cent/kw-hr):

A number of factors can affect the annual costs during any given year:

1. How many outages does the plant have - usually 1 per 12 to 24 months? Outages usually mean a lot of maintenance and high labor costs due to working around the clock.
2. How quickly a plant is being depreciated-usually 35 to 40 years
3. When the plant was built
4. NRC regulatory costs are a pass-through from the federal government.
5. Number of capital projects or modifications being done.

For other specific costs and comparisons, please check references [7]- [15].

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost Element</th>
<th>Nuclear $/Mw-hr</th>
<th>Coal $/Mw-hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Fuel</td>
<td></td>
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<td>11.0</td>
</tr>
<tr>
<td>2 Operating &amp; Maintenance - Labor &amp; Materials</td>
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<td>6.0</td>
<td>5.0</td>
</tr>
<tr>
<td>3 Pensions, Insurance, Taxes</td>
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<tr>
<td>4 Regulatory Fees</td>
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<td>5 Property Taxes</td>
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<tr>
<td>6 Capital</td>
<td></td>
<td>9.0</td>
<td>9.0</td>
</tr>
<tr>
<td>7 Decommissioning &amp; DOE waste costs</td>
<td></td>
<td>5.0</td>
<td>0.0</td>
</tr>
<tr>
<td>8 Administrative / overheads</td>
<td></td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
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</table>

Table IV. Nuclear and Coal Cost Comparisons.

9. CONCLUSIONS

Understanding how long-term and spot prices relate to one another is helpful in purchasing and trading decisions. Using the information that is logically contained in long-term price quotes provides insight into the true market expectations of sellers. Even if a robust futures market does not develop in the uranium industry, perhaps some sort of organized forward marketing mechanism will emerge in which pricing and contract terms are more open. Such a system could potentially create hedging opportunities as well as bring about transparency in forward prices. A more transparent forward market would facilitate uniformity in the forward market. Meanwhile, concepts like basis will continue to be borrowed from other markets in an effort to make sense of the reticent world of uranium contracting.

Noting the high level of activity in the forward market over the past three years, a “seller’s market buyers will scramble to secure long-term supply agreements in the face of rising spot prices. This widening basis appears to have happened when prices increased in the period between mid-2004 and mid-2005, as base prices in long-term contracts escalated more rapidly than spot prices. If spot prices were to increase too sharply, it is conceivable they would shoot past long-term prices causing “inverted” market. This occurred in the first half of 2007, when the spot price rose to a record high of $138 per pound U3O8 by June 1, 2007. When supplies become tight in the spot market, a surge in near-term demand may force spot prices over forward prices. In a falling market one might expect the basis to converge...
as the threat of future trading losses on forward deliveries is diminished. A falling market is often a “buyer’s” market and the lure of cheap spot prices forces long-term sellers to offer more aggressively. This is supported by the convergence of prices in late 2007. This has limits as producers can only sell so low without losing money. The concept of basis has become most important now that a uranium futures market is developing. Buyers and sellers of futures often live and die by the basis.

Electric utility buyers of uranium, UF₆ conversion, and SWU often purchase by open bid request for their specific needs. Such purchases can be either for a “spot” purchase, with typically one delivery within 12 months of the date of the bid request, or for multi-year purchases under a “long-term” contract. Although only a minority share of the utility industry’s uranium and enrichment services needs are procured under spot purchases, long-term uranium contracts typically have significant buyer flexibility to buy more or less (typically ±20-30%) than a nominal annual quantity specified in the contract. Therefore, it is easy for the utility to shift to more use or less use of the spot market, depending on the then-current spot market price, compared to the delivery price in the long-term contract. Enrichment contracts are most often based on covering a specified percentage of the utility’s or power plant’s requirements, which provides considerable flexibility to the buyer, but of a different sort than that of uranium contracts. UF₆ conversion contracts can provide either type of flexibility, depending on the particular contract form.

10. REFERENCES
[7] NRC Cost Comparison (NUREG-1350, Table 4, page 20 - Note-NRC costs do not reflect decommissioning, capital, waste costs)
[12] Jeffrey Lacruz’ Technical Background Report, (Discussion of various plant types and cost comparison (partial report))
[14] Goggle Search - nuclear power cost comparison

[15] Nuclear Energy Institute search engine - type in cost comparison

11. Acknowledgment
I would like to thank TradeTeh (http://www.uranium.info) and UxC for permitting me to use their price graphs in this paper.

12. Glossary of Uranium Industry Terms
These are terms that are commonly used in the uranium industry and the nuclear fuel cycle (ref http://www.world-nuclear.org) and the nuclear fuel cycle (refer http://www.world-nuclear.org/TradeTech & World Nuclear Association)

Actinide: An element with atomic number of 89 (actinium) to 103. Usually applied to those above uranium-93 and higher (also called transuranics). Actinides are typically radioactive with long half-lives. They are therefore significant in wastes arising from nuclear fission, e.g. used fuel.

Atom: A particle of matter that cannot be broken up by chemical means. Atoms have a nucleus consisting of positively charged protons and uncharged neutrons of about equal mass. The positive charges on the protons are balanced by a number of negatively charged electrons in motion around the nucleus.

Boiling water reactor (BWR): A common type of light water reactor (LWR), where water is allowed to boil in the core, thus generating steam directly in the reactor vessel, which in turn, drives a turbine generator directly before being recirculated in the reactor.

CANDU: Canadian deuterium uranium reactor, moderated and (usually) cooled by heavy water.

Chain reaction: A reaction that stimulates its own repetition, in particular where the neutrons originating from nuclear fission cause an ongoing series of fission reactions.

Cladding: The metal tubes containing oxide fuel pellets in a reactor core.

Control rods: Devices to absorb neutrons so that the chain reaction in a reactor core may be slowed or stopped by inserting them further, or accelerated by withdrawing them.

Conversion: Chemical process that converts uranium oxide (U₃O₈) into uranium hexafluoride (UF₆) to prepare for the enrichment process.

Coolant: The liquid or gas used to transfer heat from the reactor core to the steam generators or directly to the turbine-generators.

Core: The central part of a nuclear reactor containing the fuel elements and any moderator.

Critical mass: The smallest mass of fissile material that will support a self-sustaining chain reaction under specified conditions.

Criticality: Condition of being able to sustain a nuclear chain reaction.

 Decommissioning: Removal of a nuclear facility (reactor) from service, followed by safe storage, dismantling, and making the site available for unrestricted use.

Depleted uranium: Uranium having less than the natural content of 0.7% U-235. As a by-product of enrichment in the fuel cycle, it generally has 0.25-0.30% U-235, the rest being U-238.
**Enriched uranium**: Uranium in which the proportion of U-235 (to U-238) has been increased above the natural 0.7%. Reactor-grade uranium is usually enriched to about 3.5-5% U-235, whereas weapons-grade uranium is more than 90% U-235.

**Enrichment**: Physical process of increasing the proportion of U-235 to U-238. (See also SWU)

**Enrichment Tails**: Depleted uranium hexafluoride with less than 0.7% U-235.

**Fast breeder reactor (FBR)**: A fast neutron reactor configured to produce more fissile material than it consumes, using fertile material such as depleted uranium in a blanket around the core.

**Fast neutron reactor**: A reactor with no moderator that uses fast neutrons. It normally burns plutonium while producing fissile isotopes in fertile material such as depleted uranium (or thorium).

**Fission**: The splitting of a heavy nucleus into two, accompanied by the release of a relatively large amount of energy and usually two or more neutrons. It may be spontaneous, but usually is due to a nucleus absorbing a neutron and thus becoming unstable.

**Fuel assembly**: Structured collection of fuel rods or pins, the unit of fuel in a reactor.

**Fuel fabrication**: Making reactor fuel assemblies, usually from sintered UO₂ pellets that are inserted into zircalloy tubes, comprising the fuel rods or pins.

**Half-life**: The period required for half of the atoms of a particular radioactive isotope to decay and become an isotope of another element.

**Heavy water**: Water containing an elevated concentration of molecules with deuterium ("heavy hydrogen") atoms.

**Heavy water reactor (HWR)**: A reactor that uses heavy water as its moderator, such as the Canadian CANDU (pressurized HWR or PHWR).

**High-level wastes**: Extremely radioactive fission products and transuranic elements (usually other than plutonium) in spent (used) nuclear fuel. They may be separated by reprocessing the used fuel, or the spent fuel containing them may be regarded as high-level waste.

**Highly enriched uranium (HEU)**: Uranium enriched to at least 20% U-235.

**High-level waste (HLW)**: Highly radioactive material arising from nuclear fission. It can be what is left over from reprocessing spent (used) fuel, though some countries regard spent (used) fuel itself as HLW. It requires very careful handling, storage, and disposal.

**In-situ recover (ISR)**: The recovery by chemical leaching of minerals from porous orebodies without physical excavation. Also known as in-situ leaching and solution mining.

**Light water reactor (LWR)**: A common nuclear reactor cooled and usually moderated by ordinary water.

**Low-enriched uranium (LEU)**: Uranium enriched to less than 20% U-235. (Uranium in commercial reactors is typically 3.5-5.0% U-235.)

**Low-level waste (LLW)**: Mildly radioactive material usually disposed of by incineration and burial.

**MegaWatt (MW)**: A unit of power, \(= 10^6 \) watts. MWe (megawatts electric) refers to electric output from a generator.

**Mill Tailings**: Ground rock remaining after particular ore minerals (i.e., uranium oxides) are extracted.

**Milling**: Process by which minerals are extracted from ore, usually near a mine site.

**Mixed-oxide fuel (MOX)**: Reactor fuel that consists of both uranium and plutonium oxides, usually about 5% Pu, which is the main fissile component.

**Natural uranium**: Uranium with an isotopic composition as found in nature, containing 99.3% U-238, 0.7% U-235 and a trace of U-234. Can be used as fuel in heavy water-moderated reactors.

**Nuclear reactor**: A device in which a nuclear fission chain reaction occurs under controlled conditions so that the heat yield can be harnessed or the neutron beams utilized. All commercial reactors are thermal reactors, using a moderator to slow down the neutrons.

**Oxide fuels**: Enriched or natural uranium in the form of the oxide UO₂, used in many types of reactor.

**Plutonium**: A transuranic element, formed in a nuclear reactor by neutron capture. It has several isotopes, some of which are fissile and some of which undergo spontaneous fission, releasing neutrons. Weapons-grade plutonium is produced in special reactors to give >90% Pu-239, reactor-grade plutonium contains about 30% non-fissile isotopes. About one third of the energy in a light water reactor comes from the fission of Pu-239, and this is the main isotope of value recovered from reprocessing used fuel.

**Pressurized water reactor (PWR)**: The most common type of light water reactor (LWR), using water at very high pressure in a primary circuit and forming steam in a secondary circuit, which is subsequently used to drive a turbine-generator.

**Reactor pressure vessel**: The main steel vessel containing the reactor fuel, moderator, and coolant under pressure.

**Reprocessing**: Chemical treatment of spent (used) reactor fuel to separate uranium and plutonium and possibly transuranic elements from the small quantity of fission product wastes, leaving a much-reduced quantity of high-level waste.

**Separative Work Unit (SWU)**: This is a complex unit that 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. The unit is strictly designated kilogram Separative Work Unit, and it measures the quantity of separative work (indicative of energy used in enrichment) when feed and product quantities are expressed in kilograms. About 100-120,000 SWU are required to enrich the annual fuel loading for a typical 1,000 MWe light water reactor (LWR). Enrichment costs are related to electrical energy used. The gaseous diffusion process consumes about 2,400 kWh per SWU, while gas centrifuge plants require only about 50-60 kWh/SWU.

**Spent fuel**: Used fuel assemblies removed from a reactor after several years use and treated as waste.

**Uranium (U)**: A mildly radioactive element with two isotopes that are fissile (U-235 and U-233) and two isotopes that are fertile (U-238 and U-234). Uranium is the basic fuel of nuclear energy.
Uranium hexafluoride (UF₆): A compound of uranium that is a gas above 56°C and is thus a suitable form in which to enrich the uranium.

Uranium oxide concentrate (U₃O₈): The mixture of uranium oxides produced after milling uranium ore from a mine, sometimes referred to as “yellowcake.”

Zircaloy: Zirconium alloy used as a tube to contain uranium oxide fuel pellets in a reactor fuel assembly.

13. Appendix I (Uranium Companies)
A partial list of uranium explorers and producers are the following companies (ref. [3,5]):

1. Cameco (NYSE: CCJ, TSX: CCO)
2. Mega Uranium (TSX: MGA)
3. Energy Metals Corp. (TSX: EMC)
4. BHP Billiton (NYSE: BHP)
5. Khan Resources (TSX: KRI)
6. Paladin Resources Ltd. (TSX: PDN)
7. Blue Sky Uranium (CDNX: BSK)
8. Denison Mines Corp. (TSX: DML, AMEX: DNN)
9. First Uranium Corp. (TSX: FIU)
10. SXR Uranium One (TSX: SXR)
11. ESO Uranium Corp. (TSX-V: ESO)
12. UrAsia Energy Ltd. (TSX-V: UUU)
13. Uranium City Resources (CDNX: UCR)
14. UR Energy (TSX: URE)
15. Uranerz Energy Corp. (AMEX: URZ)