CHAPTER 11

NUCLEAR FUEL: MYTHS AND REALITIES

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The revival of interest in nuclear power, apparent over the past few years, can be explained by a combination of three factors. First, the improvement in the perceived economic viability of running nuclear reactors to generate electricity (indicated by the renewed interest of the financial sector); second, the contributions that more nuclear power may make towards curbing global carbon emissions; and third, by its possible role in enhancing energy security of supply.This return to the spotlight for nuclear has not been without some controversy, and one area that has come under scrutiny is the fuel necessary to run the power reactors. There are some important questions worthy of detailed discussion, such as will there be enough uranium to satisfy rising future requirements (especially if the number of reactors doubles or even quadruples), does an increased quantity of nuclear fuel constitute a proliferation risk, could rising uranium prices threaten the economic viability of nuclear, and are the procedures within the nuclear fuel cycle adequate to protect workers and the general public from any possible incremental health risks? These are just some more obvious examples, but unwelcome answers could serve to prevent the inchoate nuclear renaissance from coming to fruition.

THE NUCLEAR FUEL CYCLE

The most obvious point to make about the supply of nuclear fuel is that the underlying fuel cycle is rather complex, especially by comparison with the supply of such fossil fuels as coal, oil, and gas for electricity generating stations. Oil goes to a sophisticated refinery where the crude is divided into separate distillates to service the needs for electricity, transportation, and chemicals. In common with coal and gas, it is just a matter of getting it out of the ground, then onto a ship or train or into a pipeline to reach the generating station where it is burned to create the heat which drives the turbines. Nuclear is also a "thermal" mode of generating power, relying on heat, with much of a plant very similar to the fossil fuel powered stations. It is the process used to create the heat—nuclear fission rather than combustion—and the required fuel with its attendant production cycle which are distinctive.

The key features of the nuclear fuel cycle (see Figure 11-1) are worthy of some initial discussion.[1] Uranium is mined (via processes which give rise to waste streams, mainly tailings) and then converted, usually enriched (for 90 percent of the reactors around the world, the process entails increasing the share of the U-235 isotope beyond the natural 0.7 percent and creating depleted uranium of lower assay) before being fabricated into fuel to be introduced to the reactor. This phase is termed the "front end" of the cycle, before the generation of electricity in the reactor, is the most important stage as it brings in the only revenue—the sale of billions of kilowatt hours of electricity necessarily supports all the other activities, in the absence of any government subsidies.

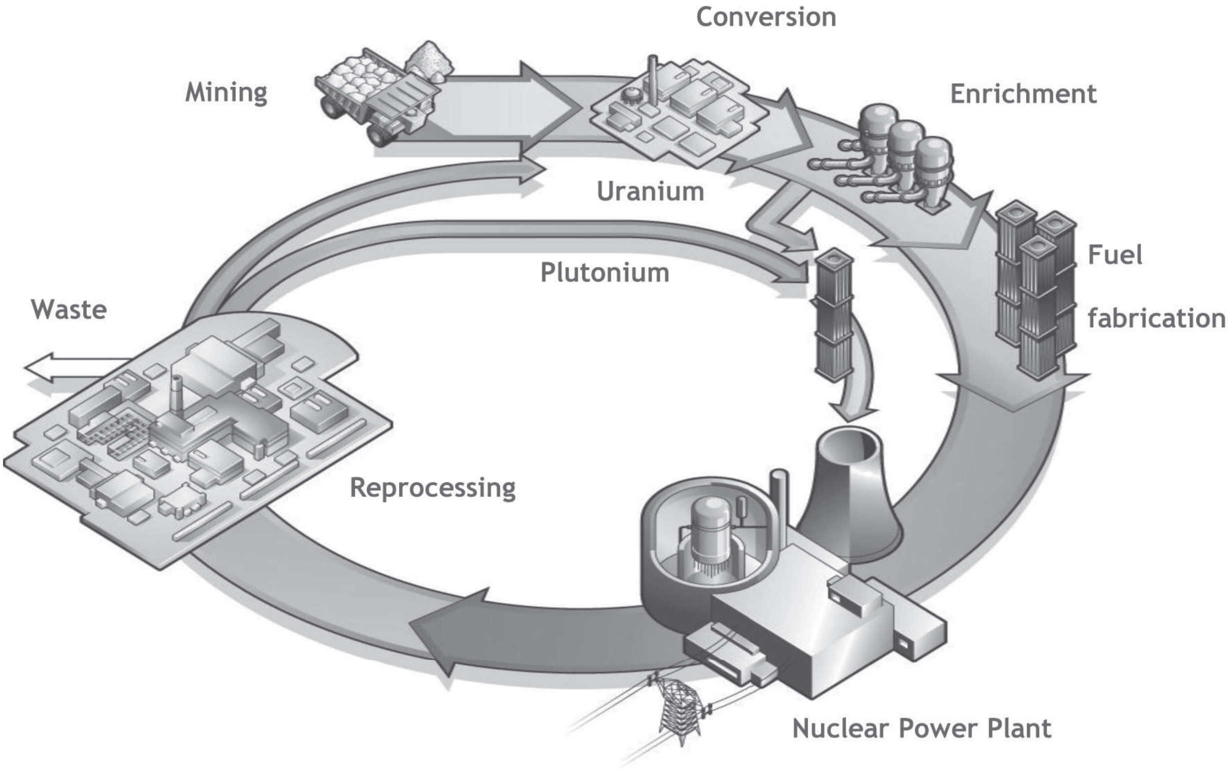


Figure 11-1. The Nuclear Fuel Cycle.

When the used fuel is unloaded from the reactor, it must initially be stored for cooling, but then there are effectively two choices regarding the "back end" of the cycle. Figure 11-1 shows a "closed" nuclear fuel cycle, with the used fuel going to a reprocessing plant. Here usable uranium and plutonium can be separated out and then recycled within the cycle to supplement supplies of fresh uranium, in the form of reprocessed uranium (RepU) and mixed oxide (MOX) fuel, respectively. What cannot be recycled becomes a waste stream from the reprocessing plant and can be vitrified (encased in plastic) before being stored "temporarily" in advance of disposal in a deep geological repository. The alternative "closed" cycle skips the reprocessing stage, with all the used fuel from the reactor immediately regarded as waste and therefore stored before final disposal.

There are several additional things worthy of note at this stage. First, although the volume and mass of the materials within the fuel cycle are tiny by comparison with the fossil fuels used to generate an equivalent amount of electricity, they do not dissipate in the atmosphere through combustion. Since the beginning of the nuclear age in the 1940s, just over 2 million metric tons of uranium have been mined, initially for nuclear weapons and after 1970 largely for civil nuclear power. We can still identify where nearly all of this is located today. Most (well over half) is in the form of depleted uranium, the second most plentiful form is used fuel from reactors, while the remainder is held in a variety of other forms, in many cases for potential future use. Historical uranium production therefore remains highly relevant to the nuclear fuel business today because material still containing fissile isotopes can potentially be processed for re-entry into the fuel cycle. The economics as well as the politics of recycling are the limiting factors. For example, there are acute political pressures to reduce the large quantities of military surplus highly enriched uranium (HEU) and military plutonium by using them as fuel in civil nuclear power reactors. Use of HEU presents few technical difficulties and has already become a major secondary supply. With the importance of historical production, the nuclear fuels business bears some similarity to precious commodities such as gold and diamonds being that these are rarely destroyed, so stockpiles and other secondary supplies are important.

Another notable feature is that the contractual arrangements normally used within the nuclear fuel market are peculiar when compared with trading in other energy commodities. With most reactors being refueled at intervals of 1 year or more, the demand for nuclear fuel is “lumpy” rather than continuous, as it is for the fossil fuels. Plant operators or their procurement agencies usually contract either directly or indirectly via intermediaries with uranium mining companies for the supply of uranium concentrates. They then have this uranium processed into a usable form through separate agreements with conversion, enrichment, and fuel fabrication suppliers. The obvious question is why they do not simply buy the fabricated fuel? Although there are moves today to offer a complete “cradle to grave” fuel package (maybe even taking on responsibilities for the “back end”), most buyers prefer to buy the four components—uranium, conversion, enrichment, and fuel fabrication—separately. This is for a variety of historical, economic, and (some would say) self-interested reasons. Hence four separate markets exist.

Another important feature of the nuclear fuel cycle is its international dimension. Uranium is relatively abundant throughout the earth’s crust, but distinct trade specialization has occurred, due partly to the high energy density and therefore the low costs of transportation, as compared with coal, oil, and gas. For example, uranium mined in Australia can be converted in Canada, enriched in the United Kingdom, then fabricated as fuel in Sweden for a German reactor. Recycled reactor fuel may follow similar international routes, with related political as well as economic implications. With relative ease of transport and storage, inventories are an important feature of the nuclear fuel business. On the other hand, in the past there have been notable trade restrictions that have impacted the market, while today various constraints on transporting fissile materials have become an important issue.

THE IMPORTANCE OF NUCLEAR FUEL

Ready availability of nuclear fuel is obviously important because, without it, the reactor will not run and generate electricity. So any delays and disruption to the timely arrival of the fabricated fuel at the reactor will be fatal. Yet, despite the complications of the fuel cycle outlined above, the possibilities of regulatory hindrances, and the potential for political, trade, or transport difficulties, there are very few cases where fuel has failed to reach reactors. The international nuclear fuel market is clearly somewhat imperfect, but it has always performed well in its basic function of supplying reactors. One obvious recent instance of fuel not getting to reactors is that of India, where nonproliferation restrictions and India's poor domestic uranium supply situation combined to prevent reactors from running at full capacity.

Nuclear fuel is quite a big business. Table 11-1 shows a rough calculation of the cost of 1kg of enriched uranium, present and ready to be loaded into a reactor.

Uranium	9.0 kg U308	$25 per lb	495
Conversion	7.6 kg U	$13 per kg	99
Enrichment	7 SWU	$135 per SWU	945
Fabrication	1 kg	$300 per kg	300
Total			$1839

Table 11-1. Cost of 1kg of Nuclear Fuel.

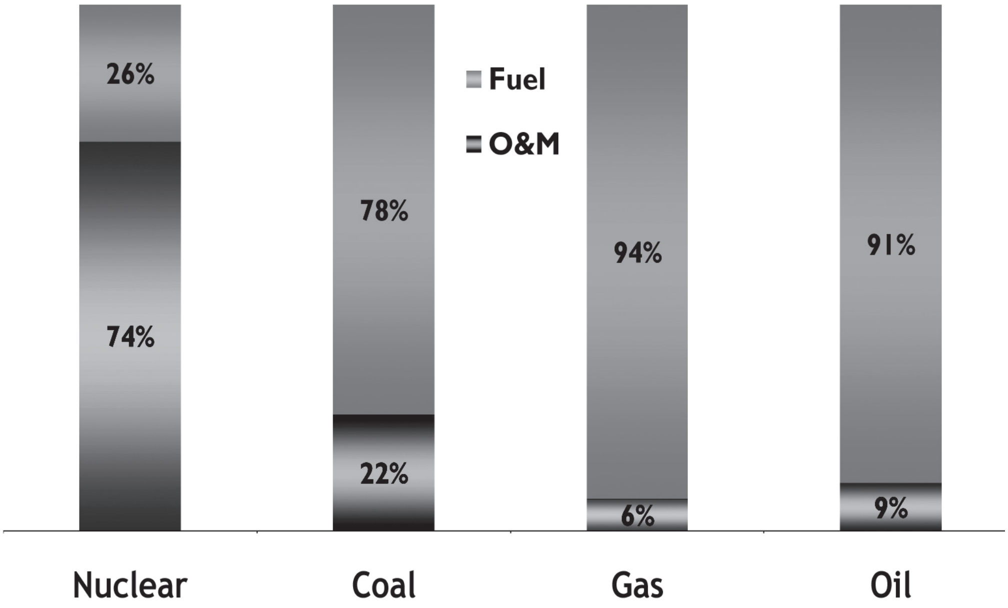
To refuel a large 1GWe reactor on an annual basis, about 20 tons of enriched uranium are needed, at a total cost of about $40 million. Multiplying by the 400-plus reactors in operation around the world and adjusting for their size gives a world market for nuclear fuel of $15-20 billion on an annual basis, depending of course on the contract prices. This is a small figure by comparison with the coal, oil, and gas trade, but is still a significant business, employing many thousands of people.

A significant paradox surrounds nuclear waste—it offers the biggest advantage of nuclear power, but at the same time, arguably, its greatest handicap. On one hand, the small amount of uranium required to produce a huge amount of nuclear energy leaves a correspondingly small amount of solid waste which, as far as the industry is concerned, can be safely contained and managed without environmental harm. Because nuclear fuel supplies are relatively inexpensive and highly energy-intensive (and thus small in volume), they can readily be stockpiled, affording a major buffer against energy insecurity. Finally, because fuel represents a small proportion of the generating costs of nuclear power, relative price stability for power is assured regardless of price fluctuations.

On the other hand, those opposed to nuclear power have identified the small volume of nuclear waste as its Achilles heel. As yet, there are no operating repositories for high-level waste (HLW), and there remains a very lively debate, both within and outside the industry, on the merits and demerits of reprocessing, which creates in turn additional public affairs debates. Additionally, in the oil and gas industry, the importance of fuel means that big and powerful companies like Shell, BP, Exxon, and Total are able to devote huge resources to massaging their corporate reputations. With the exception of BP, of course, given its travails over the Gulf of Mexico oil spill, this results to some extent in a generally favorable public image of their industry. The reputation of nuclear has undoubtedly suffered because its fuel business is not so significant—the largest uranium producer, Cameco, is tiny by comparison with the oil giants. Most companies in nuclear are involved in other, sometimes mutually competitive, energy sectors too, and with the exception of Areva in France, are not as yet profitable and powerful enough to massage their image into a favorable industry reputation.

But in an economic sense, the relatively low cost of fuel (and indeed its relative stability) is nuclear's key card to play. On all the other elements of the cost structure of generating electricity, nuclear is disadvantaged—from the capital cost of the plants and the time it takes to build them, to the operating and maintenance (O&M) costs of running them, to the costs of eventually decommissioning the facilities and returning the sites to alternative use. In addition, nuclear projects are often regarded as relatively risky by investors, and the cost of securing finance may well be higher than for other energy-related ventures, too.

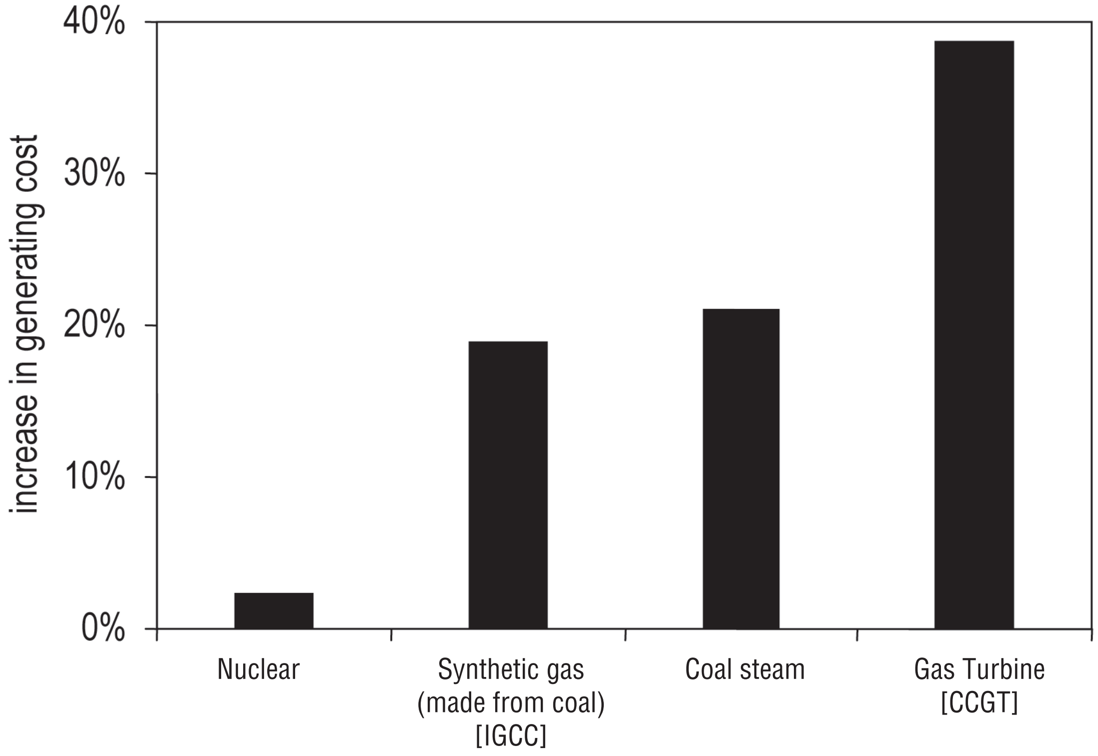
The relatively low cost of nuclear fuel includes, in addition to the "front end" costs outlined above, a full contribution to the cost of waste management, which is prescribed by national rules. But for nuclear plants already in operation, the fuel cost is a relatively small part of generating costs, at around a quarter (see Figure 11-2).[2] The costs of operating oil- and gas-powered electricity generating plants derive almost entirely from the fuel price while the profits of coal-powered plants, too, are significantly affected by the cost of coal. Despite some movements up and down in the price of uranium, the nuclear fuel cost has remained very stable over time. However, the reactor fuel buyers fight hard to save every last cent because this is cost they feel they can influence. Where they are selling power in competitive markets, they cannot pass on increased fuel prices to customers, and higher prices will directly hit profits.



Source: Global Energy Decisions, ERI, Inc.

Figure 11-2. Fuel as a Share of Electricity Generating Costs, Current Plants in USA.

When it comes to new nuclear plants, their economics are even less sensitive to the fuel cost, as shown in Figure 11-3. The economics of new nuclear **DEPENDS** heavily on the capital cost of the plant and the rate of interest, with fuel costs playing only a relatively minor role. Once a nuclear plant is started up, the economics depend on it running 24 hours a day/7 days a week, with long periods (sometimes now up to 24 months) between shutdowns for maintenance and refuelling.



Source: IEA WEO 2006, reference case.

Figure 11-3. Impact of 50 Percent Increase in Fuel Cost on Generating Cost, New Plants.

URANIUM IS NOT GEOLOGICALLY SCARCE

One of the great myths perpetuated about nuclear power is that uranium is scarce in a geological sense, on a par with diamonds, gold, and other precious metals. It is true, however, that (rather like gold) a significant amount of emotion surrounds its discovery and exploitation. Indeed, there was a uranium rush in the western United States in the 1950s, on a par with the Californian gold rush of the late 19th century, often mythologized in "B" movies depicting fathers and sons going prospecting in the badlands.

The reality is a little different.[3] Uranium is a slightly radioactive metal that occurs throughout the Earth's crust, about 500 times more abundant than gold, 40 times than silver, and about as common as tin, tungsten, and molybdenum. It occurs in most rocks in concentrations of two to four parts per million, for example, at about four parts per million (ppm) in granite, which makes up 60 percent of the earth's crust. In fertilizers, uranium concentration can be as high as 400 ppm (0.04 percent), and some coal deposits contain uranium at concentrations greater than 100 ppm (0.01 percent) (fertilizer and coal ash exploitation for uranium has been viable in the past and may conceivably be so again). It is also found in the oceans, at an average concentration of 1.3 parts per billion. The Japanese, and possibly others, have seriously studied possible extraction from seawater.

The bigger issue is one of economics. Apart from the 1950s, the late 1970s, and once again today, uranium prices have been relatively low, thus limiting usable deposits where to extraction is economically feasible. Economics is certainly related to the percentage of uranium in the ore (the grade), but that is only part of the story. The depth below the surface, geological setting, and a variety of other factors are also important. Uranium occurs in a number of different igneous, hydrothermal, and sedimentary geological environments, with deposits world-wide having been grouped into 14 major categories, based on geological setting. When mined, it yields a mixed uranium oxide product, (U_3O_8) which is yellow in color. Uraninite or pitchblende is the most common uranium mineral.

For many years from the 1940s, virtually all the uranium mined was used in the production of nuclear weapons, but this ceased to be the case in the 1970s. Today the only substantial use for uranium is as fuel in nuclear reactors, mostly for electricity generation. Uranium-235 is the only naturally-occurring material which can sustain a fission chain reaction, releasing large amounts of energy.

Plenty of Uranium to Fuel Any Conceivable Nuclear Future.

There is every reason to expect that the world supply of uranium is sustainable, with adequate proven reserves being continuously replenished at costs affordable to consumers. Speculation to the contrary represents a misunderstanding of the nature of mineral resource estimates and reflects a short-term perspective overlooking continuing advances in knowledge and technology and the dynamic economic processes that drive markets.

Concerns about limitations of the Earth's resources go back more than a century. Although they appear intuitive and logical on the basis that mined mineral resources are clearly finite and physically nonrenewable, analysis in most cases shows that encountering limits to the supply of resources lies so far in the future that present-day concerns have little practical meaning. There are, however, examples such as oil, where prices may now be indicating that proven reserves are indeed beginning to run out. Concerns about resource depletion therefore deserve careful examination.

Characteristically, dire predictions of scarcity based on published proven mineral reserve figures have faltered by taking inadequate account of “resource-expanding factors,” namely, gains in earth knowledge and discovery capabilities, gains in mining technology, and changes in mineral economics.

To achieve sustainability, the combined effects of mineral exploration and technology development need to discover proven recoverable reserves at least as fast as they are being used. Historical data teach this important lesson regarding most minerals. Reserve margins for metals, stated in terms of multiples of current use, have been continuously replenished or—more often—increased. On average, real prices for metals, including uranium, have tended to fall over time. It is important to recognize—with any commodity at any time—that one should never expect to see proven reserves of more than a few decades’ worth because exploration will take place only if companies are confident of gaining a financial return. The prospect of a return is usually dictated by strong prices flowing from the prospect of imminent undersupply. When this happens, there tends to be a strong surge of exploration effort, yielding significant new discoveries. Weak uranium prices have held back exploration for much of the nuclear age—increased prices in recent years have led to a renewed exploration boom with the sudden appearance of over 400 “junior” uranium companies raising money through initial public offerings. These are already leading to upgrades in uranium resource estimates.

Today annual requirements to fabricate fuel for current power reactors call for about 65,000 tons of uranium. According to the authoritative Nuclear Energy Agency (NEA)-International Atomic Energy

Agency (IAEA) "Red Book,"[4] the world's present proven reserves of uranium, exploitable at below $80 per kilogram of uranium, are some 3.5 million tons. This proven reserve is therefore enough to last for 50 years at today's rate of usage—a figure higher than for many common metals. Current estimates of all expected uranium resources (including those not yet economic or properly quantified) are six times as great, representing 300 years' supply at today's rate of usage.

It cannot be overemphasized that these numbers, though providing a favorable prospect, almost surely understate future uranium availability because proven reserves of most minerals bear little relationship to what is actually in the outer part of the Earth's crust and potentially extractable for use. Proven reserves are an unrealistic indicator of what will actually be available in the long term. At most, they are useful as a guide to what is available for production in an immediate future spanning no more than a few decades. In the case of current proven reserves of uranium, the 50-year quantification is no more than a rear-view mirror perspective on supply. During future consumption of these reserves, the dynamics of supply and demand will produce price signals that inevitably trigger effects involving all three of the "resource-expanding factors" cited above. This is already evident in today's uranium market.

Additional Supplies of Nuclear Fuel.

As noted below, up to 40 percent of recent world uranium demand has been filled by so-called secondary supplies from military and civilian stockpiles or from reprocessing of used fuel. In the period since 1985, excessive commercial inventories have been consumed as East-West arms control efforts began to dictate substantial dismantling of nuclear warheads, yielding commercially usable fissile material. These secondary supplies will remain an important part of the market for some years to come, but they are clearly limited, as their source is previously-mined uranium. As secondary supplies are depleted, primary uranium production will pick up strongly to fill their place.

It should also be noted that the element thorium, which is even more abundant in the Earth's crust than uranium, constitutes an additional potential source of nuclear fuel. Although thorium is not fissile, it is "fertile"—i.e., capable of being converted into fissile U-233—and technologies for making this conversion are already well advanced in some places, notably India.

LOWER URANIUM USE

Even with the current stock of operating nuclear reactors, there are ways of saving on uranium if prices rise, reflecting market scarcity due, perhaps, to production problems. It is possible to increase the amount of enrichment services in a given quantity of enriched uranium by varying the assay of the waste stream (the "tails assay"—see below), while reactor operating cycles can also be adjusted to make savings. Reactor design is, however, continuously developing. Evolutionary light-water reactor designs, which are all more fuel-efficient than their predecessors, will be the mainstay of nuclear programs over the next decade. However, in the period beyond 2030, advanced reactor designs such as those included in multinational research programs (Generation IV and INPRO) represent a further step forward in fuel efficiency.[5]

Some advanced reactor designs are fast-neutron types, which can utilize the U-238 component of natural uranium (as well as the 1.2 million tons of depleted uranium now stockpiled). When such designs are run as "breeder reactors"—with the specific purpose of converting non-fissile U-238 to fissile plutonium—they offer the prospect of multiplying uranium resources 50-fold, thereby extending them into a very far distant future. Others will be "burners" configured to utilize much of the world's used nuclear fuel inventory as future reactor fuel.

It may therefore be fairly concluded that uranium supplies will be more than adequate to fuel foreseeable expansions of nuclear power, even if the number of reactors runs into the thousands compared with the hundreds today. Indeed, in addition to its other noteworthy virtues, an abundant fuel resource will remain a crucial advantage of nuclear power. Those investors currently considering nuclear power are, of course, perfectly aware of this. It is somewhat curious why many of those opposed to nuclear power focus on the imaginary weakness of limited supply, when supply is actually plentiful. But ultimately, if investors are happy to put their money into new reactors, it is their problem, not the public's, if the reactors run out of fuel.

Future Nuclear Generating Capacity.

The magnitude of future nuclear fuel demand depends on two factors: first, the number and size of reactors in operation (nuclear generating capacity); and second, how they are run (key operating parameters). In reality, nuclear generating capacity is by far the most important factor, and efforts to forecast the future of nuclear power concentrate heavily on it.[6]

The two main aspects to forecasting nuclear generating capacity are the outlook for the continued operation of existing plants and the prospects for the construction of new reactors. How long existing reactors will, in fact, remain in operation depends on a number of factors, which vary from country to country. The most important of these are the licensing procedures applying to life extensions and the economic attractiveness of continued operation. The latter will depend partly on the state of the electricity market in which the reactor is operating; that is, the price for which the plant's output can be sold, the types of electricity supply contracts permitted, the availability of capital for construction of replacement generating capacity, etc. Environmental (e.g., the avoidance of carbon dioxide emissions) and security of energy supply considerations may also influence reactor lifetimes in the future.

In principle, extending the lifetime of existing nuclear plants should normally be economically attractive. Nuclear power is characterized by high initial capital costs and low fuel costs, with operations and maintenance (O&M) costs varying according to operator efficiencies and regulatory practices. For well-managed plants with low O&M costs, the cost of producing electricity will be very competitive. The licensing obstacles to be overcome for life extension vary significantly from country to country. In the United States, reactor operating licenses are limited to 40 years of operation, but a procedure has been adopted by the Nuclear Regulatory Commission (NRC) to consider applications for life extensions. Most U.S. reactor operators have applied for and/or given notice that they will apply for life extensions for the operating licences. Some industry commentators have predicted that over 90 percent of the U.S. reactors could apply for and be granted life extensions to 60 years.

In some other countries, the situation regarding licenses is more flexible, with no fixed lifetime. So long as the regulatory authorities are satisfied that a reactor is safe, it can continue to operate. Of course, regulators may insist on additional checks on older plants, and may require upgrades to be carried out. But such requirements may be imposed at any time, and are not linked to a fixed nominal lifetime.

Life extensions, however, may be only one side of the coin. There is nothing which guarantees that reactors will operate even for their nominal 40-year lifetime if their operating costs are too high or if they encounter licensing or political problems. Even if operating costs are not too high, a closure decision may come because a plant requires major additional capital expenditure to keep it in operation (for example, steam generator replacement). The cost of servicing the additional capital, added to existing costs, may make the plant uneconomic.

There have already been individual instances where operable plants have been closed permanently well short of their intended lifetime, either because the utility judged that the cost of power generated was or would become too high, or because of failure to secure necessary licenses for their renewals. Politics have also unfortunately intruded here. The United States and Germany have been particularly affected by closures owing to economic factors, although no U.S. plants have closed since 1998. The Swedish government forced the premature closure of reactors in 1999 and 2005 for political reasons. Also in a political move, the German government enacted a law in April 2002 effectively limiting the operating lifetime of nuclear power plants. The highly economic nature of nuclear generation in Germany may, however, prompt a reversal of this if political change is forthcoming. The expense and possible adverse environmental effects of providing replacement power may prove significant.

A final factor to consider when discussing existing plants is the potential available for up-rating their capacity by capital expenditure on the plant, such as modifying the steam generators and/or replacing the turbine generator set. Several countries have already benefited from this, notably Finland, Germany, Spain, Sweden, Switzerland, and the United States, and it may represent a highly economic way of generating more power in many others. For example, some U.S. reactors are now up-rating their power output by up to 20 percent as part of plans to seek extensions for total operating lives of 60 years. Power up-rates in boiling water reactors (BWRs) tend to be much larger than in pressurized water reactors (PWRs), owing to the greater ease of changing the size of the fuel array.

Estimating the likely number of new reactors is particularly challenging, given the wide range of important factors to consider. It is reasonable to divide the likely new reactors over the next 25 years or so into three groups:

1. Those currently under construction around the world, which currently amounts to about 40;
2. Those for which a significant amount of planning, financing, and approval activity has already taken place, currently about 100; and,
3. Those which have been proposed, but without any commitment of significant funds towards financing and approval, currently up to 300.

The degree of uncertainty as to completion of reactors obviously increases in the third category. The usual approach to projecting numbers is to build scenarios based on different mixes. This is the approach of the World Nuclear Association (WNA), which offers three country-level scenarios to 2030:

1. A reduced-scope scenario in which many existing reactors do not operate beyond currently licensed lives and there are very few new reactors—indeed, some of those under construction today are never completed.
2. A reference scenario, where most existing reactors get some extensions to their operating licenses and there are increasing numbers of new reactors, particularly after 2020, comprising those under construction and planned, plus a few of those merely proposed.
3. An increased-scope scenario, in which many reactors run for 60 years and there are large numbers of new reactors, including all those planned and many of those currently merely proposed.

In reality, the picture for overall world nuclear generating capacity (and effectively the demand for nuclear fuel) depends on a few major countries. Despite the possibility of many new countries getting nuclear power, by 2020 there are unlikely to be more than five to add to the 30 countries which currently do. By 2030, there could conceivably be a much larger additional number,[7] but nuclear generating capacity will be driven by what happens in the United States; some major European countries like the United Kingdom, Germany, and Russia; and the big developing countries, China and India.

Figure 11-4 shows the WNA world nuclear generating capacity scenarios to 2030. Up to 2020, there is not a major difference between the scenarios as there are relatively few reactor closures in even the lower scenario. The number of new reactors which can come into operation by 2020 is somewhat limited by the time it takes to license and construct new reactors (an allowance of 4 years for each of these stages is customary, meaning 8 years in total). After then, significant numbers of reactors go out of service in the lower scenario (there were over 200 current reactors completed in the 1980s), while the reference and upper scenarios show large numbers of new reactors. By 2030, the scenarios diverge markedly, with nuclear generating capacity in the upper scenario roughly double today's level at 720 gigawatts (GWe), but less than 300 GWe in the lower case. However, because world electricity generation is also expected by the International Energy Agency (IEA) to double by 2030, even the upper scenario will not increase the share of nuclear from the current 15 percent.

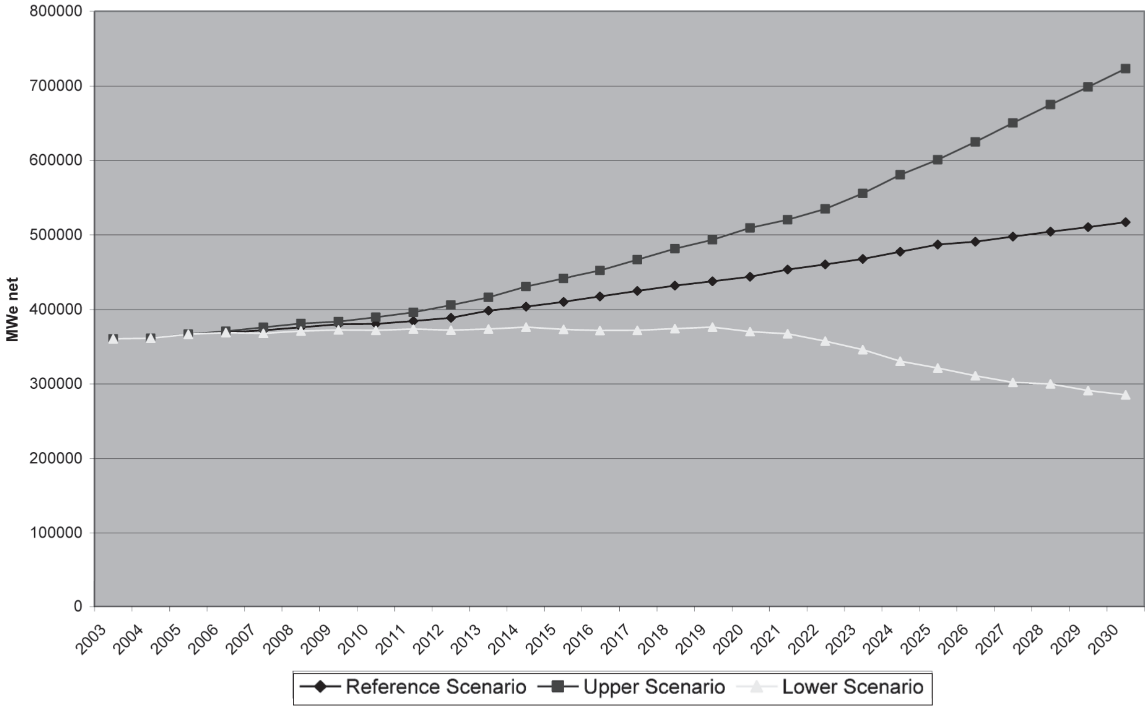


Figure 11-4. WNA World Nuclear Generating Capacity Scenarios.

FUTURE NUCLEAR FUEL DEMAND

The generating capacity scenarios can form the basis of similar ones for complete fuel demand (uranium, conversion, enrichment, and fuel fabrication). These require a computer-based model for the calculations, using the key parameters (such as the reactor load factor, the enrichment level, the fuel burn-up, and the tails assay at the enrichment plant). Perhaps the most important of these is the tails assay, that is, the measure of the amount of fissile uranium (U-235) remaining in the waste stream from the uranium enrichment process. There is a link between uranium and enrichment services, to the extent that they are at least partial substitutes. To obtain supplies of enriched uranium, required for 90 percent of all commercial nuclear reactors, fuel buyers can alter the quantities of uranium and enrichment services by varying the contractual tails assay at the enrichment plant. When uranium becomes relatively more expensive, there is an incentive to supply less of it and use more enrichment, thus "extracting" more U-235 from each pound. When uranium prices were around U.S.$10 per pound, the optimum tails assay was about 0.35 percent, but with the quadrupling of uranium prices since 2003 and a much smaller upward movement of enrichment prices, the optimum is now around 0.25 percent. Assuming such price relativities are sustained into the long term (which is arguable), there could be a substantial (20 percent or more) increase in enrichment demand and a corresponding fall in the requirements for fresh uranium. The major limitation on this dynamic is the availability of surplus enrichment capacity—constraints on this have so far limited the possibility of buyers to take full advantage.

Nevertheless, higher uranium prices are undoubtedly a positive inducement for future enrichment demand and will no doubt be taken into account in the coming major plant investment decisions.

Figure 11-5 shows the WNA world uranium requirements scenarios to 2030. The shape of the scenarios is, of course, very similar to those for generating capacity, with the lower scenario very robust until 2020, after which demand begins to diminish with reactor closures. This consistency of uranium demand is unusual among metal commodities, which usually suffer from significant demand cycles—with nuclear, however, once a reactor starts up, it tends to run for many years. The reference and upper scenarios both show rapidly rising uranium demand beyond 2015. The growth rates are actually slightly ahead of the growth of generating capacity because the fuel enrichment levels and the load factors of the reactors (essentially the percentage of time they are on-line) are both expected to rise from the levels of today.

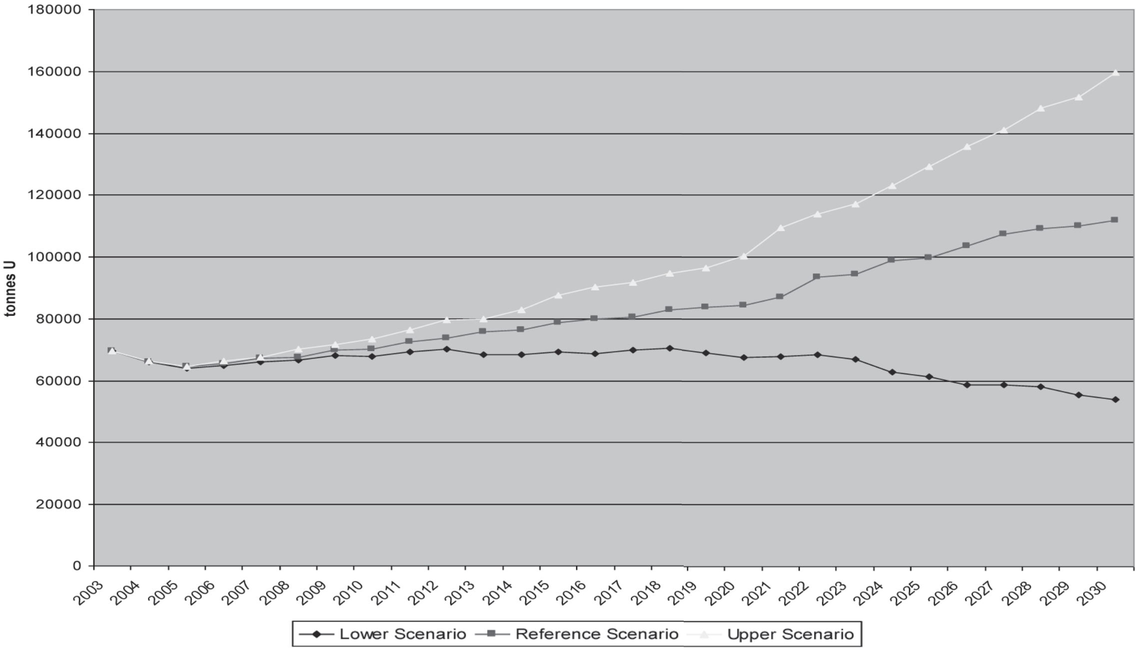


Figure 11-5. WNA Scenarios for World Uranium Requirements.

HISTORICAL URANIUM PRODUCTION

Figure 11-6 shows the peaks and troughs of uranium production in the western world since 1945 and also plots the level of demand to feed commercial reactors. It is clear that supply and demand are not always in sync. The difference can be explained by there being essentially “four ages of uranium”:

1. A military age, from 1945 to the late 1960s. Uranium demand from this source fell sharply from 1960 onwards and, in response, production halved by the mid 1960s.

2. An age of rapidly expanding civil nuclear power, lasting from the late 1960s to the mid 1980s. Production peaked in 1980 and stayed above annual reactor requirements until 1985.

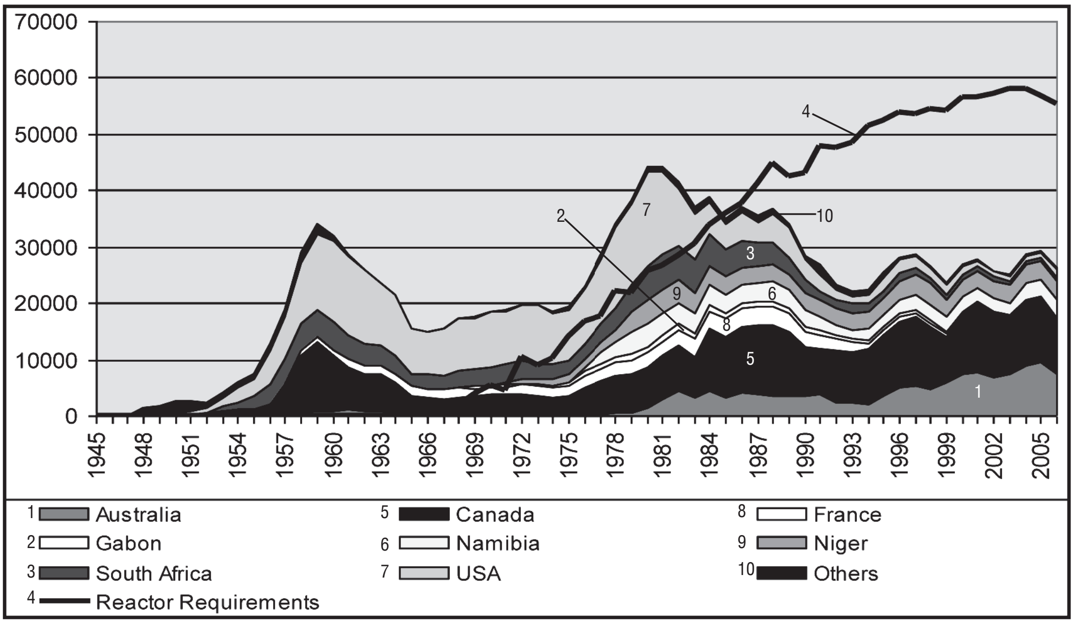
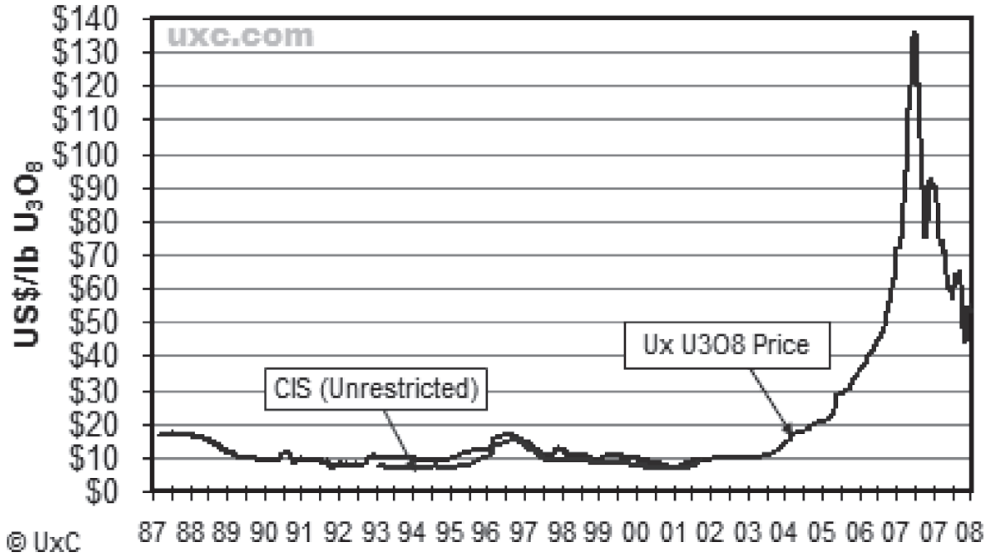


Figure 11-6. Western World Uranium Production and Reactor Requirements in Tons Uranium.

3. An age dominated by an inventory overhang, extended by supply from the former Soviet Union, lasting from the mid-1980s up to 2003.

4. From 2003, a strong market reaction to the perception that additional primary production is needed to support accelerating nuclear growth and to offset declining and finite secondary supplies.

The gap between production and demand is still apparent today, but it is beginning to close as the so-called "secondary supplies begin to diminish in significance. The third age, "inventory overhang," led to a long depression in the uranium price, shown in Figure 11-7. This led to production becoming concentrated in a small number of major mines in a limited number of countries, with Canada and Australia producing around half of the world total by the early years of this century. The significant price reaction since 2003 (the fourth age) is discussed in more detail below, but has had the effect of stimulating exploration and plans for new mine development. Kazakhstan is the rising world producer and is set to overtake Canada as the leader by 2010. Production is also now rising in Africa, with increases in Namibia, Niger, and Malawi, with Malawi now expecting its first mine opening. Plotting future production against the demand scenarios for uranium has to take into account the secondary supplies of uranium as shown in Figure 11-8.



* Commonwealth of Independent States

Figure 11-7. Spot Uranium Prices.

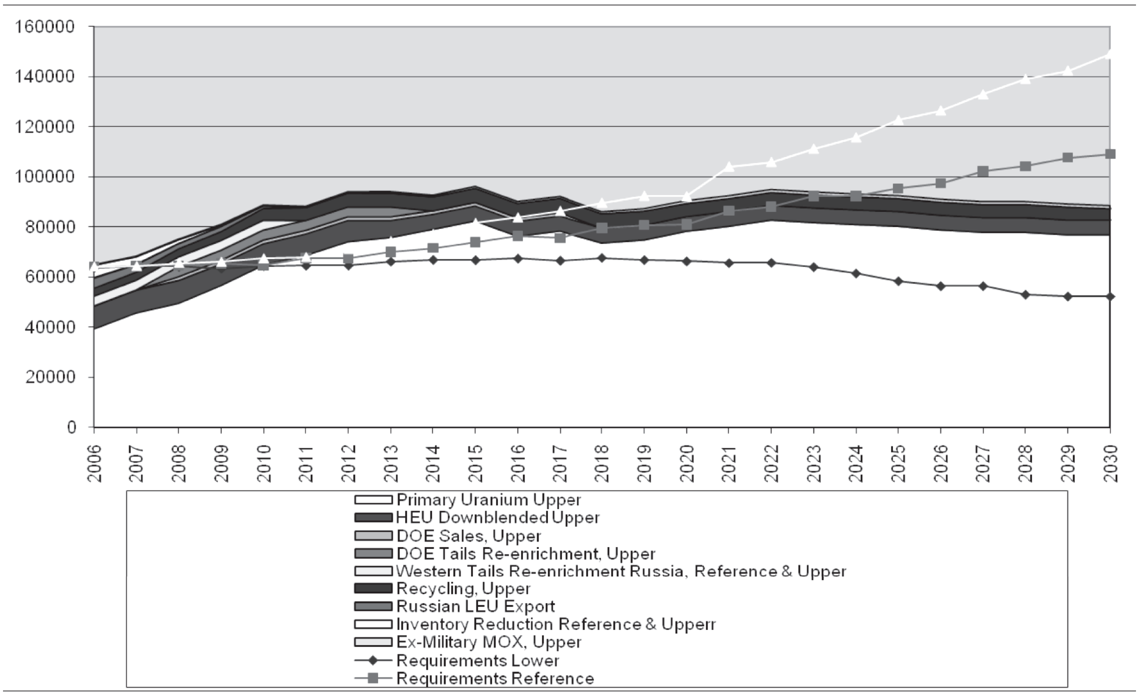


Figure 11-8. Reference Case Supply and Uranium Demand Scenarios.

Primary uranium production must now rise from around 40,000 tons worldwide to 60,000 tons to satisfy market demand. Beyond 2020, however, it is currently hard to predict where and when new mines will open, but with the reference and upper demand cases, world production will have to rise to 80,000 tons and beyond, double today's level.

It is believed that there are now over 400 junior uranium companies, the overwhelming majority still at the exploration stage. Few are yet moving towards mine development, but the front-runners, such as Paladin and Uranium One, are already producing and growing rapidly. Moreover, a high degree of consolidation is beginning to take place amongst these companies. Some are being acquired by the established producers (such as UraMin by Areva) but the better-established juniors are also acquiring each other—Uranium One's successive acquisitions of Southern Cross, UrAsia, and Energy Metals are particularly notable.[8]

MINING TECHNIQUES AND THE ENVIRONMENT[9]

The decision as to which mining method to use for a particular deposit is governed by the nature of the ore body, safety, and economic considerations. Excavation may be either underground or open pit mining. In the case of underground uranium mines, special precautions, consisting primarily of increased ventilation, are required to protect against airborne radiation exposure. But in many respects uranium mining is much the same as any other mining. Projects must have environmental approvals prior to commencing, and must comply with environmental, safety, and occupational health conditions applicable.

Increasingly, these are governed by international standards, with external audits.

Milling, which is generally carried out close to a uranium mine, extracts the uranium from the ore. Most mining facilities include a mill, although where mines are close together, one mill may process the ore from several mines. Milling produces a uranium oxide concentrate which is shipped from the mill, usually referred to as "yellowcake," and generally contains more than 80 percent uranium. The original ore may contain as little as 0.01 percent uranium. The residue, containing most of the radioactivity and nearly all the rock material, becomes tailings, which are deposited in engineered facilities near the mine (often in mined-out pits). Tailings contain long-lived radioactive materials in low concentrations and toxic materials such as heavy metals; however, the total quantity of radioactive elements is less than in the original ore, and their collective radioactivity will be much shorter-lived. These materials need to be isolated from the environment.

Conventional mining will remain important (for example, the huge Olympic Dam deposit in South Australia is currently an underground mine, but the owner, BHP Billiton, is investigating a four-fold expansion as an open pit from about 2015). But an increasing proportion of the world's uranium now comes from in situ leaching (ISL).[10] This technique involves leaving the ore where it is in the ground, and using liquids which are pumped through it to recover the minerals from the ore by leaching (i.e., dissolving out soluable target constituents by percolation). If there is significant calcium in the ore body (as limestone or gypsum), alkaline (carbonate) leaching must be used, otherwise, acid (sulfate) leaching is generally better.

There is little surface disturbance, and no tailings or waste rock are generated. However, the orebody needs to be permeable to the liquids used, and located so that they do not contaminate groundwater. About a quarter of world uranium production is now by ISL (including nearly all the rapidly-rising Kazakh output). Techniques for ISL have evolved to the point where it is a controllable, safe, and environmentally benign method of mining which can operate under strict controls.

SECONDARY SUPPLIES STILL IMPORTANT

Secondary supplies may be defined as all materials other than original, out-of-earth products sourced to satisfy reactor requirements. They include inventories, the draw-down of surplus military stockpiles, and other recycled materials of various types. In the widest sense, secondary supplies may be regarded as previous uranium production, returned to the commercial nuclear fuel market. Uranium production historically has not been closely correlated with actual reactor fuel requirements, leading to cycles of substantial inventory buildup and then disposal. In particular, there was a substantial buildup of commercial inventories in the late 1970s and early 1980s, when production rose sharply at a time when many reactor projects were being cancelled. The subsequent gradual exhausting of these inventories depressed the uranium market for many years.

Much of the secondary supply reaching the market in recent years has been down-blended highly enriched uranium (HEU) from military stockpiles declared surplus by arms limitation treaties.[11] A deal between Russia and the United States involving Russian stockpiles has satisfied roughly half of the U.S. nuclear fuel requirements since the deal's commencement in the mid-1990s and has also substantially contributed to important nonproliferation goals. The commercial terms, however, are now judged by the Russians to be unfavorable, as they were signed at a time when the Russians needed hard currency (whereas today they have lucrative oil and gas export earnings). They have now announced that there will be no renewal after the current deal expires in 2013. There will, however, be substantial quantities of surplus Russian HEU available for down-blending in the period beyond 2013, so it is reasonable to expect that it will be mostly employed to meet internal needs such as fueling Russian-origin reactors both at home and in export markets such as China and India. The United States also has some quantities of HEU which are surplus to military requirements, which will likely enter the commercial nuclear fuel market at some point in the future.

Finally, the reprocessing of used nuclear fuel is one fuel cycle option which can allow the recycling of plutonium and uranium to displace fresh uranium.[12] Programs for the recycling of plutonium were developed in the 1970s when it appeared that uranium would be in scarce supply and would become increasingly expensive. It was originally proposed that plutonium would be recycled through fast breeder reactors, that is, reactors with a uranium "blanket" but which would produce slightly more plutonium than they consume. Thus it was envisaged that the world's "low cost" uranium resources, then estimated to be sufficient for only 50 years' consumption, could be extended for hundreds of years.

As things transpired, the pressure on uranium resources was very much less than expected, and prices remained low in the period up to 2003. This was caused by the discovery of several new extensive and low-cost uranium deposits, the entry onto the world market of large quantities of uranium from the dismantling of nuclear weapons, and the slower growth of nuclear power than was expected back in the 1970s. Thus there was little incentive to develop fast breeder reactors, particularly as they present major engineering challenges which could prove expensive to resolve. Nevertheless, since the late 1970s, around 30 percent of used fuel arising from commercial nuclear reactors outside the former Soviet Union and its satellite states have been covered by breeder reprocessing contracts with plants in France and the UK.

Mixed Oxide (MOX) fuel was introduced mainly to reduce the stockpiles of plutonium, which were building up as spent fuel reprocessing contracts were fulfilled. MOX was therefore an expedient solution to a perceived problem, which had been created by changed circumstances. The MOX programs have demonstrated that plutonium has some advantages as a nuclear fuel and so the stockpiles have economic value.

Currently 12 of the countries with nuclear energy programs are committed to a closed nuclear fuel cycle, but there are signs that the number may soon increase. In particular, the United States is reassessing its previous policy, set strongly against reprocessing with subsequent recycling of recovered materials. The decision to introduce MOX fuel from ex-weapons plutonium in civil reactors was an important element in this and the first assemblies are now in use in reactors operated by Duke Power.

The "once through" cycle uses only part of the potential energy in the fuel, while effectively wasting substantial amounts of usable energy that could be tapped through recycling. In the United States, this question is pressing since significant amounts of used nuclear fuel are stored in different locations around the country awaiting shipment to the planned geological repository at Yucca Mountain in Nevada. This project is much-delayed, and, in any case, will fill very rapidly if it is used simply for used fuel rather than the separated wastes after its reprocessing.

The strong upward movement in uranium prices suggests that utilities owning inventories of reprocessed uranium (RepU) will look once again at utilizing these. The greater expense during the conversion and enrichment stages may now be outweighed by the substantially increased prices for fresh fuel. EDF, the operator of all the French nuclear plants, is at center stage here, owning significant quantities of RepU as a strategic asset. A few years ago, these could fairly be viewed on the other side of the balance sheet, as a long-term liability, but such an assessment is now outdated. Certainly many European utilities (and maybe also some in the United States) are looking at RepU in a new light and will possibly seek to add to those plants which have already gone down this road (albeit in relatively small quantities).

THE URANIUM MARKET

Most uranium is traded on the basis of multi-annual contracts, based on perceived utility requirements. The spot market in uranium is driven by shorter-term adjustments to utility procurements and by uranium production plans rather than by annual reactor requirements, with price quotes provided by traders and brokers. Unlike the case of many other commodities, there is no terminal clearing market place such as the London Metal Exchange (LME) or its equivalents, though a market for financially settled futures, involving very small quantities, has been established at NYMEX. In addition, mutual funds have been created to allow investors to buy directly in and own uranium inventories.

The market has now moved up from a long period of oversupply in the 20 years up to 2003, where hopes for new demand from additional reactors were frustrated and abundant secondary supplies pushed the price down to around \$10 per pound. Although there was plenty of industry speculation about this period's inevitable end (secondary supplies can clearly not last forever), there were few price signals until the market suddenly tightened during 2003, and a sharp price spike began. Financial speculators became interested in uranium (indeed, the price became an easy one-way bet for a time), while hundreds of small mining exploration companies added uranium to their portfolio and raised substantial sums on the stock markets.

The spot price peaked at \$137 per pound in the middle of 2007 but has since slipped back sharply, in a series of stages, to end 2008 at around \$50.[13] While volatility is a characteristic of most commodity prices, with tendencies to both over- and under-shoot deeper market fundamentals, the extent of the price decline now raises worry that projects will not go ahead and potential supply shortages could appear in the future (together with another and possibly more dramatic price spike). Everyone knows there are plenty of proven uranium resources in the ground—the question is how to get these to market in a timely manner and at prices which balance the interests of both producers and consumers in an equitable way.

This balance should really not be too difficult to achieve, as both uranium producers and reactor investors/operators have similar time horizons, with new projects going through lengthy approval stages and then taking several years in the construction stage, before running for 40 years and beyond. Reactors are generally fuelled only once per year (or longer), so that demand is discontinuous (contrast this with a coal-fired generating station). This pattern lends itself to long-term contracts, negotiated between buyer and seller, which may last for up to 20 years. These are highly confidential, and while they may reference quoted industry spot prices, they also contain escalation clauses, caps, and floors. This has been the traditional approach to selling nuclear fuel, with producers using the security of long-term contracts as collateral for raising project capital.

URANIUM CONVERSION

This enrichment process requires uranium in gaseous form, which is achieved by converting it to uranium hexafluoride (UF_6) gas at relatively low temperatures. At a conversion facility, uranium is first refined to uranium dioxide, which can be used as the fuel for those types of reactors that do not require enriched uranium. Light water reactors (LWRs) require enriched uranium as do the UK's gas-cooled reactors. Heavy water reactors (HWRs), which are mainly of the CANDU design, require conversion from natural uranium concentrates directly to UO_2.

Worldwide requirements for UF_6 conversion services, averaged over an extended period, will be equal to aggregate demand for uranium requirements after allowing for the small number of reactors which do not require conversion. Countries operating CANDUs or other HWRs with requirements for UO_2 conversion are Argentina, Canada, China, India, Korea, Pakistan, and Romania. The key to future growth in demand is the magnitude of the Indian nuclear program, which so far has relied heavily on HWRs.

Worldwide, five major suppliers meet the majority of the demand for UF_6 conversion services, namely Cameco in Canada, Converdyn in the United States, Areva in France, Westinghouse in the United Kingdom, and Rosatom in Russia. The market is therefore quite concentrated, but there is sufficient competition to avoid monopolistic abuse. With regard to UO_2 conversion supply, Cameco's plant in Canada is by far the largest supplier, with a licensed annual capacity of 2,800 tU. In addition, smaller plants exist to meet the local needs in India, Argentina, and Romania.

URANIUM ENRICHMENT

The enrichment of uranium constitutes a necessary step in the nuclear fuel cycle to fuel more than 90 percent of operating reactors worldwide.[14] The process involves increasing the isotopic level of the uranium-235 contained in natural uranium (0.711 percent) relative to the level of uranium-238 (99.3 percent). The majority of nuclear power reactors use low enriched uranium with up to 5 percent U-235. This enables greater technical efficiency in reactor design and operation, particularly in larger reactors, and allows the use of ordinary water as a moderator. The process of enriching the U-235 content to up to 5 percent is currently carried out utilizing two proven enrichment technologies, gaseous diffusion, and centrifugation. The first of these to be developed was gaseous diffusion, in which UF_6 gas is pumped through a series of diffusion membranes. The lighter U-235 passes through the porous walls of the diffusion vessels slightly faster than U-238, resulting in a higher concentration of U-235 in the product. Centrifugation is a more recent technique in which UF_6 gas is spun at high speed in a series of centrifuges. This tends to force the heavier U-238 isotope closer to the outer wall of the centrifuges, leaving a higher concentration of U-235 in the center.

The enrichment stage has traditionally represented the largest single front-end fuel cycle expense for utilities, but with the uranium price increases since 2003, the relative uranium cost has risen. The process is measured in terms of the separative work completed, defined as the amount of enrichment effort expended upon a quantity of uranium in order to increase the contained assay of U-235 by a given amount relative to that of U-238. This is measured in separative work units (SWU).

On the enrichment supply side, the most obvious feature is the gradual replacement of the old gas diffusion facilities of the U.S. Enrichment Corporation (USEC) in the United States and Areva in France with more modern and economical centrifuge plants. Even with favorable supply contracts, the huge amount of power required by the diffusion process renders it uneconomic against the centrifuges, as currently used by Urenco in Europe and by the Russian plants. Areva will gradually replace diffusion equipment with centrifuges derived from a technology-sharing agreement with Urenco, while USEC has decided to develop its American centrifuge technology, based on U.S. Department of Energy (DoE) programs in the 1970s and 1980s. Urenco and Areva are also building

U.S. plants in New Mexico and Idaho, respectively. Assuming USEC can overcome the financing and technical issues surrounding its plans, the last gas diffusion capacity should disappear around 2015 and the whole of the enrichment market should then be covered by centrifuges. The only likely alternative is the Australian SILEX laser enrichment technology, which has the support of GE-Hitachi for its possible commercial development. This latter may yet turn out to be the technology of the future, as was thought 10 years ago when USEC and others were investing significant amounts in laser technology, but its widespread commercialization (if it turns out to be technically and economically viable) may have to await the next generation of heavy investment in capacity, in the period after 2015. For the near future at least, centrifuges will be the technology of choice. The Russian centrifuge capacity is not known with any degree of accuracy, but is believed to be in the range of 25 million SWUs per year. This is believed to be rising slowly, as old centrifuges are replaced by new.

The enrichment stage in the fuel cycle creates much interest because of the possible weapons proliferation issues—the enrichment plants could be used to enrich uranium up to the levels required for a nuclear bomb, over 90 percent U-235. This topic will be considered below, but the large quantity (about 1.3 million tons worldwide) of depleted uranium (DU) from enrichment plants is also a live issue. Every ton of natural uranium produced and enriched for use in a nuclear reactor provides about 130 kilograms (kg) of enriched fuel (3.5 percent or more U-235). The balance is DU (U-238, with 0.25-0.30 percent U-235). It is stored either as UF_6 or converted back to U_3O_8, which is less toxic and more benign chemically, and thus more suited for long-term storage. Every year over 50,000 tons of depleted uranium join already substantial stockpiles in the United States, Europe, and Russia.

Some DU is drawn from these stockpiles to dilute high-enriched (>90 percent) uranium released from weapons programs, particularly in Russia, and destined for use in civil reactors. Other uses are more mundane, and depend on the metal's very high density (1.7 times that of lead). Hence, where maximum mass must fit in minimum space, such as aircraft control surfaces and helicopter counterweights, yacht keels, etc., DU has been found to be well-suited. It has also been used for radiation shielding, being some five times more effective than lead. Also because of its density, it is used as solid slugs or penetrators in armor-piercing projectiles, alloyed with about 0.75 percent titanium. This final use has caused much controversy, with the allegation that there are radiation risks when such shells explode.

FUEL FABRICATION

Little similarity exists between the workings of the uranium, conversion, and enrichment markets and that of fuel fabrication. Nuclear fuel assemblies are highly engineered products, made especially to each customer's individual specifications. These are determined by the physical characteristics of the reactor, by the fuel cycle management strategy of the utility, and national, or even regional, licensing requirements.

Many fuel fabrication companies are also reactor vendors, and they usually supplied the initial cores and early reloads for reactors built to their own designs. As the market developed, however, each fabricator began to offer reloads for its competitors' reactor designs. This has led to an increasingly competitive market for fuel. Moreover, with several suppliers competing to supply different fuel designs, a trend of continuous fuel design improvements has emerged focusing on improving performance.

Currently, fuel fabrication capacity for all types of light water reactor (LWR) fuel throughout the world exceeds the demand by a considerable amount. Outside the LWR fuel market, fuel fabrication requirements tend to be filled by facilities dedicated to one specific fuel design, usually operated by a domestic supplier. For example, all fabrication requirements for AGR and Magnox reactors in the UK are supplied by dedicated domestic facilities. CANDU fuel is also produced almost exclusively within the country where the reactor is located, by UO_2 conversion and fabrication facilities dedicated to such supply. Fuel fabrication supply is therefore less concentrated than that of conversion and enrichment.

Given the very competitive nature of the LWR fabrication business and overcapacity in supply, the industry has reorganized and now seen some mergers, possibly driven by the expectation of the apparent nuclear renaissance. For example, British Nuclear Fuels (BNFL) sold Westinghouse Electric to Toshiba, and General Electric has, as a consequence, formed a joint nuclear company with its Global Nuclear Fuels partner, Hitachi.

The mergers a few years ago were expected to result in reduction of existing over-capacities, but only production consolidation has happened so far. Some plants have even increased their capacity along with modernization and relicensing projects.

NONPROLIFERATION CONCERNS

A web of licensing, surveillance, and national and multinational regulations is in place throughout the nuclear fuel cycle to ensure that safety and nonproliferation objectives are met. This is administered by governments, by regional organizations such as Euratom Supply Agency (ESA) in the European Union (EU), and by the IAEA. Despite the evident success (as international treaties go) of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) in preventing many more countries from developing nuclear bombs, the expected expansion of nuclear power has brought forth new concerns.[15]

These concerns essentially started with the announcement from North Korea claiming it has an operating centrifuge enrichment program. There remain substantial doubts about this claim, but it was followed by further revelations from Iran and Libya showing that they had similar programs. Centrifuge enrichment technology is very difficult to master and needs high-quality plant components, but it appears that in each case, substantial progress has been made towards achieving facilities which could enrich uranium to weapons-level assays.

The common link in each of these countries has been technology transfer from the enrichment program in Pakistan, which uses old Urenco-derived centrifuge technology. This has clearly worried those concerned with weapons proliferation, although the quantities of enriched material produced and its assays remain unknown. These revelations have led to proposals for strengthening the nonproliferation regime. A big concern is that countries may develop various sensitive nuclear fuel cycle facilities and research reactors under full safeguards and then subsequently opt out of the NPT, as North Korea has done. This suggests that moving to some kind of intrinsic proliferation resistance in the fuel cycle itself is timely. There are several ideas, floated many years ago, which have been dug out and revamped. One key principle is that the assurance of nonproliferation must be linked with assurance of supply and services within the nuclear fuel cycle to any country embracing nuclear power. In addition to the need to accelerate adherence to the IAEA Additional Protocol, which ensures a stricter inspection regime, the IAEA, the United States, and Russia have proposed that enrichment facilities should be confined to the small number of countries already involved in the business. These will then offer full and fair trade to only those who accept full scope safeguards, perhaps with the provision of fuel banks and possibilities of fuel leasing. A similar regime has been proposed for spent fuel reprocessing, which also carries proliferation risks.

Those opposed to such measures see them as essentially a solution looking for a problem. The number of new nuclear countries is likely to be very limited for many years, and few countries that have moved to civil nuclear power have shown any desire to get involved in weapons. The commercial nuclear fuel market arguably works very well in securing regular supplies for any potential customer, and restrictions on supply may be deemed anti-competitive and potentially lead to higher prices.

TRADE AND TRANSPORT RESTRICTIONS

Few countries possess the full range of facilities required to carry out all steps of the nuclear fuel cycle. The degree of specialization in the nuclear fuel industry clearly contributes to the overall economic efficiency of the nuclear fuel markets, as it would be prohibitively expensive for a country with a small or fledgling nuclear power program to develop all the necessary fuel cycle facilities. Hence those that attempt to do so (for example, Brazil) naturally arouse suspicions on grounds of possible proliferation risk. They may argue, in return, that they are concerned by possible trade and transport restrictions and want to develop local natural and labor resources.

Nevertheless, it is the case today that international nuclear commerce does not face particularly onerous barriers, provided that nations fit in with the obligations imposed by the NPT. Indeed, by comparison with the trade in agricultural commodities, it can be argued that the rules and regulations in force today are not particularly onerous and should not prevent new countries from acquiring power reactors, if they wish to do so. With the general easing of governmental restrictions on nuclear material flows for political or protectionist reasons, it is concerns about transport that are now threatening the future of nuclear commerce.[16] At the very least, they impose substantial cost increases, but also threaten security of supply. They are being addressed by establishing a better dialogue between government, industry, and the contractors themselves. Both port and carrier shipments need to be freed up in order to provide the confidence that is needed for a sound industry future.

SUMMARY AND CONCLUSIONS

There is clearly sufficient uranium in reserve to fuel any conceivable expansion of nuclear power over the next few decades, and the costs of nuclear fuel are unlikely to be material in the decision whether to go ahead with new reactor plans. The key feature of the nuclear fuel market over the coming period is likely to be the ability of primary uranium production to expand rapidly, despite the continued important part which secondary supplies will play. With firmer world uranium prices, it has now become easier for primary producers to compete with the remaining secondary supplies, the production costs of which are largely sunk. Much consolidation has already taken place within the uranium production industry, and new uranium projects nearly always face various delays and frustrations before getting into production.

Within the conversion, enrichment, and fuel fabrication sectors, there are interesting market developments, but capacities appear likely to be sufficient to cope with demand. The enrichment sector is facing a technology shift in the period to 2015, by when it is generally expected that the older gas diffusion technology will have been replaced by centrifuges. During the years of poor fuel prices, the supply infrastructure in the industry was badly neglected, and this damage is at last being repaired so as to cope with escalating demand.

Looking to the very long term, beyond 2030, there is the promise of new reactor designs making fundamental changes to the nuclear fuel business. In particular, they may act as an effective solution to disposing of the substantial quantities of used nuclear fuel around the world, as many designs are characterized as “burners.” Uranium, conversion, and enrichment requirements, as we currently know them, may gradually pass into history.

ENDNOTES - CHAPTER 11

1. For further detail on the fuel cycle, see World Nuclear Association, "The Nuclear Fuel Cycle," available from *www.world-nuclear.org/info/inf03.html*.

2. This point is made well in the chapter on nuclear power in *World Energy Outlook 2006*, Washington, DC: International Energy Agency, 2006.

3. This and the following sections draw heavily on a WNA paper on uranium sustainability, World Nuclear Association, "Uranium: sustaining the Global Nuclear Renaissance?" September 2005, available from *www.world-nuclear.org/reference/position_statements/uranium.html*.

4. *Uranium 2007: Resources, Production & Demand*, Washington, DC: Organization for Economic Cooperation and Development (OECD)-Nuclear Energy Agency (NEA) and International Atomic Energy Agency (IAEA), 2008.

5. World Nuclear Association, "Generation IV Nuclear Reactors," updated June 2010, available from *www .world-nuclear.org/info/inf77.html*.

6. World Nuclear Association, *The Global Nuclear Fuel Market: Supply and Demand 2009-2030*, London, UK: World Nuclear Association, 2009.

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9. World Nuclear Association, "Environmental Aspects of Uranium Mining," September 2009, available from *www.world-nuclear.org/info/inf25.html*.

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13. The Ux Consulting Company, “UxC Nuclear Fuel Price Indicators (Delayed),” available from *www.uxc.com/review/uxc_Prices.aspx*.

14. World Nuclear Association, “Uranium Enrichment,” updated June 2010, available from *www.world-nuclear.org/info/inf28.html*.

15. World Nuclear Association, “Safeguards to Prevent Nuclear Proliferation,” updated May 2010, available from *www.world-nuclear.org/info/inf12.html*.

16. World Nuclear Association, “Transport of Radioactive Materials,” January 2010, available from *www.world-nuclear.org/info/inf20.html*.