Nuclear Fuel – Myths and Realities

By Steve Kidd*

The revival of interest in nuclear power, apparent over the past few years, can be explained by a combination of three factors. Firstly the improvement in the perceived economic viability of running nuclear reactors to generate electricity (indicated by the renewed interest of the financial sector) and then also the contributions that more nuclear power may make towards both curbing global carbon emissions and to 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 answers in the negative could serve to hinder the mooted nuclear renaissance.

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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 the fossil fuels, coal, oil and gas, for electricity generating stations. Although oil goes to a sophisticated refinery (where the barrel is divided into separate elements 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, 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’s the process used to create the heat, nuclear fission rather than combustion, and the required fuel with its attendant production cycle which is distinctive.

The key features of the nuclear fuel cycle (see Figure 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% of the reactors around the world, increasing the share of the U-235 isotope beyond the natural 0.7% and creating depleted uranium of lower assay) before being fabricated into fuel to be introduced to the reactor. This is termed the “front end” of the cycle, before the generation of electricity in the reactor. This is the most important stage as it is this which 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 or any alternative kindly benefactor.

[1] Further detail on the fuel cycle is provided at http://www.world-nuclear.org/info/inf03.html

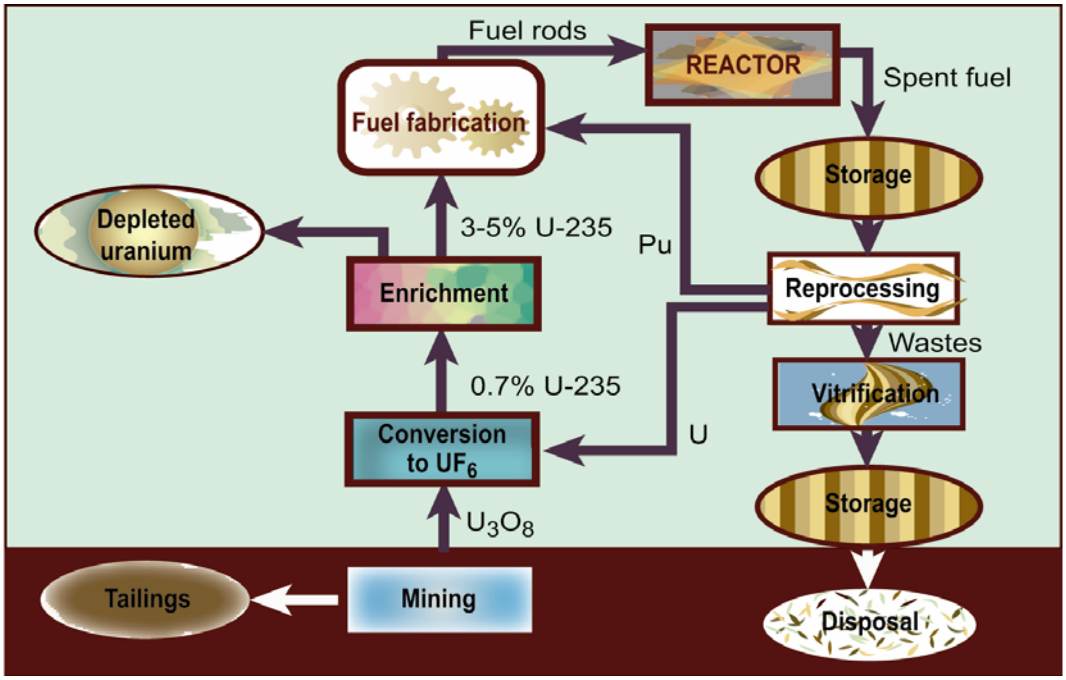


Figure 1: The nuclear fuel cycle

When the used fuel is unloaded from the reactor, it must initially be stored for cooling, but then there are effectively two choices in the "back end" of the cycle. Figure 1 shows a "closed" nuclear fuel cycle, with the used fuel going to a reprocessing plant. Here useable uranium and plutonium can be separated 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 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. Firstly, 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 tonnes of uranium has been mined, initially for nuclear weapons and after 1970 largely for civil nuclear power, and 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 largest element 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 as 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 source of secondary supply. With the importance of historical production, the nuclear fuels business bears some similarity to precious commodities such as gold and diamonds as 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 a peculiarity when compared with trading in other energy commodities. With most reactors being refueled at intervals of one year or more, the demand for nuclear fuel is “lumpy” rather than continuous as it is for the fossil fuels. Then plant operators or their procurement agencies usually contract either directly or indirectly via intermediaries with uranium mining companies for the supply of uranium concentrates, then have this uranium processed into a useable form through separate agreements with conversion, enrichment and fuel fabrication suppliers. The obvious question is why they don’t simply buy the fabricated fuel and, although there are moves 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 separately. This is for a variety of historical, economic and (some would say) self-interested reasons. Hence separate markets for uranium, conversion, enrichment and fuel fabrication 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 their 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, there have in the past 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

At a trite level, 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 and possibilities of regulatory concerns or political, trade or transport difficulties intervening , 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. The obvious recent instance of fuel not getting to reactors is that of India, where non-proliferation restrictions meant that reactors could not run at full capacity owing to India's poor domestic uranium supply situation.

We can show, as well, that nuclear fuel is quite a big business. Table 1 shows a rough calculation of the cost of 1kg of enriched uranium, ready to be loaded into a reactor

Table 1: Cost of 1kg of nuclear fuel

Uranium	9 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

In order to refuel a large 1GWe reactor on an annual basis, about 20 tonnes of enriched uranium is needed, so the cost will be 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 coal, oil and gas trade, but is still a significant business, employing many thousands of people.

There is, however, a significant paradox surrounding nuclear fuel – it is both the biggest advantage of nuclear power, but at the same time arguably its greatest handicap. 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 (see below) 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.

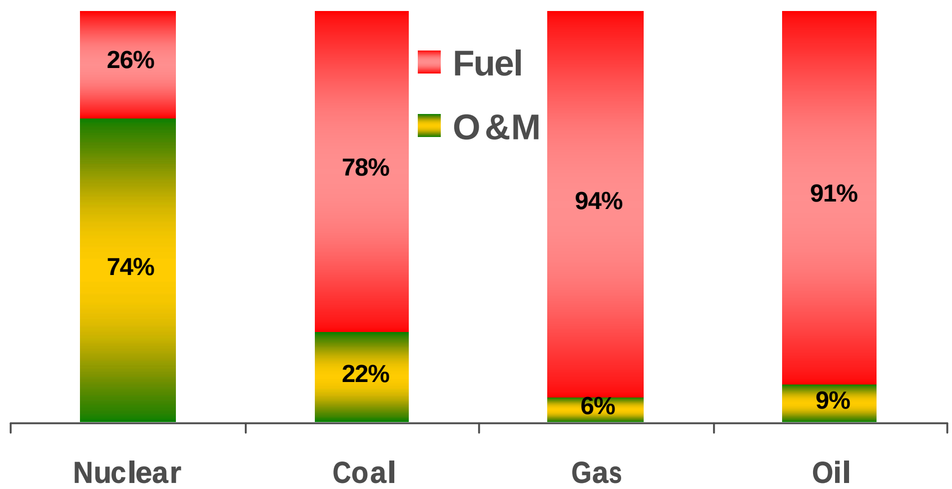
On the other hand, those opposed to nuclear power have identified the small volume of nuclear waste as its Achilles heel. As yet, there are no operating repositories for high-level waste (HLW) and there remains a very live debate, both within and outside the industry, on the merits or otherwise of reprocessing, which itself creates 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. This rubs off, to some extent, in a generally favourable 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 competitive, energy sectors too and with the exception of Areva in France, are not (as yet) powerful enough to leverage their own image onto industry reputation.

But in an economic sense, the relatively low cost of fuel (and indeed its relatively 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, the operating and maintenance (O&M) costs of running them and 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 fuel 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. For nuclear plants already in operation, the fuel cost is a relatively small part of generating costs, at around a quarter (see Figure 2).[2] The economics of operating oil and gas generating plants swings almost entirely on the fuel price while coal plants, too, are heavily dependent 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 over which they feel they have some degree of sway. Where they are selling power in competitive markets, they cannot pass on increased fuel prices to customers and higher prices will directly hit profits.

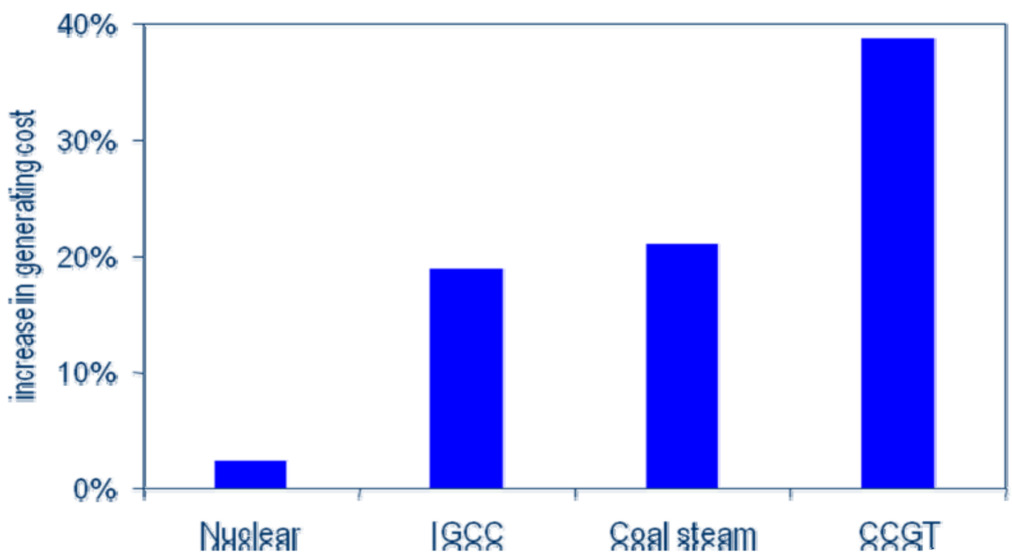
When it comes to new nuclear plants, their economics are even less sensitive to the fuel cost, as shown in Figure 3. The economics of new nuclear swing heavily on the capital cost of the plant and the rate of interest, with fuel costs playing only a relatively minor role. Once a nuclear plant is started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

[2] This point is made well in the chapter on nuclear power in World Energy Outlook 2006 – International Energy Agency



Source: Global Energy Decisions, ERI Inc

Figure 2: Fuel as a share of marginal generating costs, current plants in USA



Source: IEA WEO 2006, reference case

Figure 3: Impact of 50% increase in fuel cost on generating cost, new plants

Uranium is not geologically scarce

One of the great myths perpetrated 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) there's a significant amount of emotion around 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, which was somewhat mythologized in "B" movies, depicting fathers and sons going prospecting in the badlands at weekends.

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 as 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% of the earth's crust. In fertilisers, uranium concentration can be as high as 400 ppm (0.04%), and some coal deposits contain uranium at concentrations greater than 100 ppm (0.01%) (fertiliser and coal ash exploitation of uranium has been viable in the past and may conceivably be so again in the future). It is also found in the oceans, at an average concentration of 1.3 parts per billion and the Japanese, at least, have seriously studied possible extraction from seawater.

The bigger issue is one of economics. Apart from during the1950s, the late 1970s and once again today, uranium prices have been relatively low and have limited the

[3] This and the following sections draw heavily on a WNA paper on uranium sustainability: http://www.world-nuclear.org/reference/position_statements/uranium.html

known deposits where extraction is economically feasible. Economics is certainly related to the concentration 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 and deposits world-wide have 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 colour. Uraninite or pitchblende is the most common uranium mineral.

For many years from the 1940s, virtually all of the uranium that was 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 that overlooks continuing advances in knowledge and technology and the dynamic economic processes that drive markets.

Concerns about limitations on 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 not renewable, in most cases careful analysis shows that limits to the supply of resources are so far away that 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 the technology development need to be creating proven reserves at least as fast as they are being used. Historic data teaches the important lesson that this has regularly occurred, and continues to occur, with 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 recognise – with any commodity at any time – that one should never expect to see proven reserves of more than a few decades because exploration will only take place if companies are confident of making a financial return. The prospect of 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 finance on stock markets. These are already leading to upgrades in uranium resource estimates.

Today annual requirements to fabricate fuel for current power reactors amount to about 65,000 tonnes of uranium. According to the authoritative NEA-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 tonnes. 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 overemphasised that these numbers, though themselves providing a favourable 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 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 will inevitably trigger effects involving all three

[4] Uranium 2007 : Resources, Production & Demand (2008) – OECD-NEA and IAEA

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% 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 run down and East-West arms control began to achieve 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” – 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 and evolutionary light-water reactor designs, which are all more fuel-efficient than their predecessors, will be the mainstay of nuclear programmes over the next decade. However, in the period beyond 2030, advanced reactor designs such as those included in multinational research programmes (Generation IV and INPRO) represent a further step forward in fuel efficiency.[5] Some advanced reactor designs are fast-neutron types, which can utilise the U-238 component of natural uranium (as well as the 1.2 million tonnes 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 and thereby extending them into a very far distant future. Others will be configured as "burners" and be set 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 an imaginary weakness when it is, in fact,

[5] Generation IV reactors are discussed at http://www.world-nuclear.org/info/inf77.html

a strength. Ultimately, if investors are happy to put their money into new reactors, it is surely their problem if the reactors run out of fuel.

Future nuclear generating capacity

The magnitude of future nuclear fuel demand depends on two factors, firstly the number and size of reactors in operation (nuclear generating capacity) and secondly 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 this. [6]

There are two main aspects to forecasting nuclear generating capacity: 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: the price for which the plant's output can be sold, the types of electricity supply contract which are 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.

[6] This and the following sections draw on The Global Nuclear Fuel Market: Supply and Demand 2007-2030 (2007) – World Nuclear Association

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 forty years of operation but a procedure has been adopted by the Nuclear Regulatory Commission (NRC) to consider applications for life extensions. Most reactor operators in the US 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% of the US 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 then 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 even operate 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 plants have closed in the United States since 1998. The Swedish government forced the premature closure of reactors in 1999 and 2005 for political reasons. 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, but it may represent a highly economic way of generating more power in many others. For example, in the United States, some reactors are now up-rating their power output by anything up to 20% 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 level 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 as follows –

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

The degree of uncertainty on completion of reactors obviously diminishes in the final category and the usual approach is to build scenarios based on different mixes. This is the approach of the World Nuclear Association (WNA), which builds up three country-level scenarios to 2030 as follows –

- A lower scenario where 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.
- 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 proposed.
- An upper scenario, where 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) swings on a few major countries. Despite the possibility of many new countries getting nuclear power, by 2020 there are unlikely to be more than 5 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 and Germany, Russia and the big developing countries, China and India.

Figure 4 shows the WNA world nuclear generating capacity scenarios to 2030. Up to 2020, there isn't 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, meaning 8 years in total is usual). 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 GWe, but less than 300 GWe in the lower case. One point worth making, however, is that 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%.

[7] For a discussion of some of the likely candidates, see http://www.world-nuclear.org/info/inf102.html

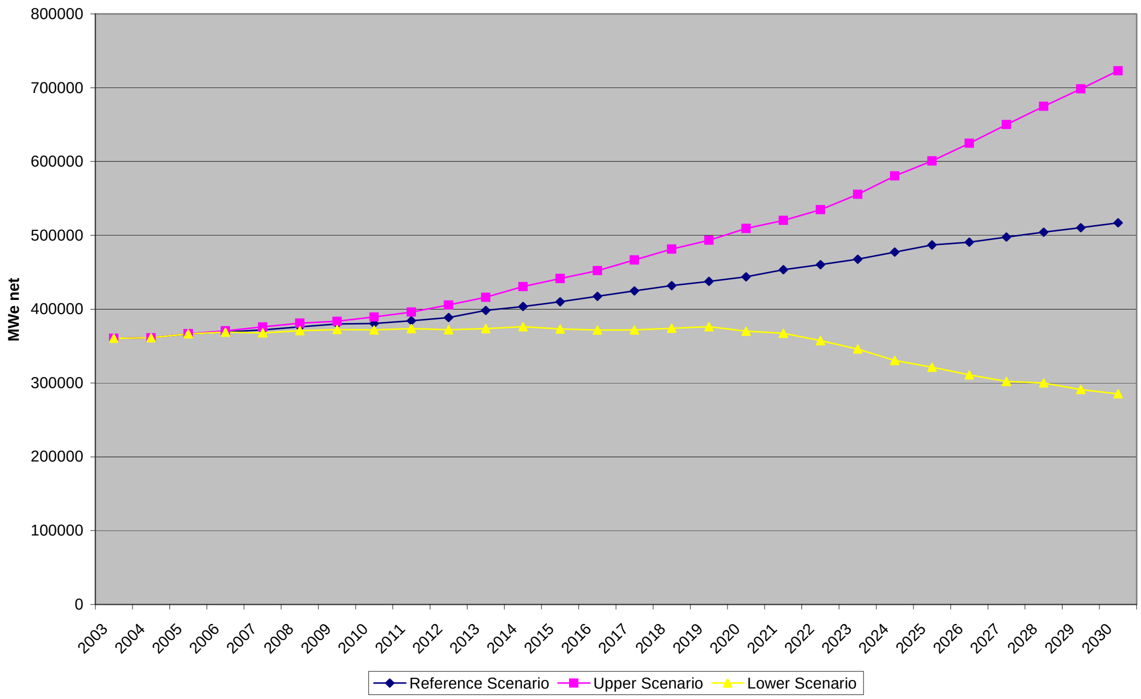


Figure 4: WNA world nuclear generating capacity scenarios

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. There is a link between uranium and enrichment services, to the extent that they are at least partial substitutes. In order to obtain supplies of enriched uranium, required for 90% ofl 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 this and use more enrichment, thus “extracting” more U-235 from each pound. When uranium prices were around US$10 per pound, the optimum tails assay was about 0.35% 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%. Assuming such price relativities are sustained into the long term (which is arguable), there could be a substantial (20% and above) increase in enrichment demand and a corresponding fall in the requirements for fresh uranium. The major limitation on this 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 feature for future enrichment demand and will no doubt be taken into account in the coming major plant investment decisions.

Figure 5 shows the WNA world uranium requirements scenarios to 2030. The shape of the scenarios is not surprisingly very similar to those for generating capacity, with the lower scenario very robust until 2020, after which demand begins to fall away with reactor closures. This consistency of uranium demand is unusual amongst metal commodities which usually suffer from significant demand cycles – with nuclear, 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

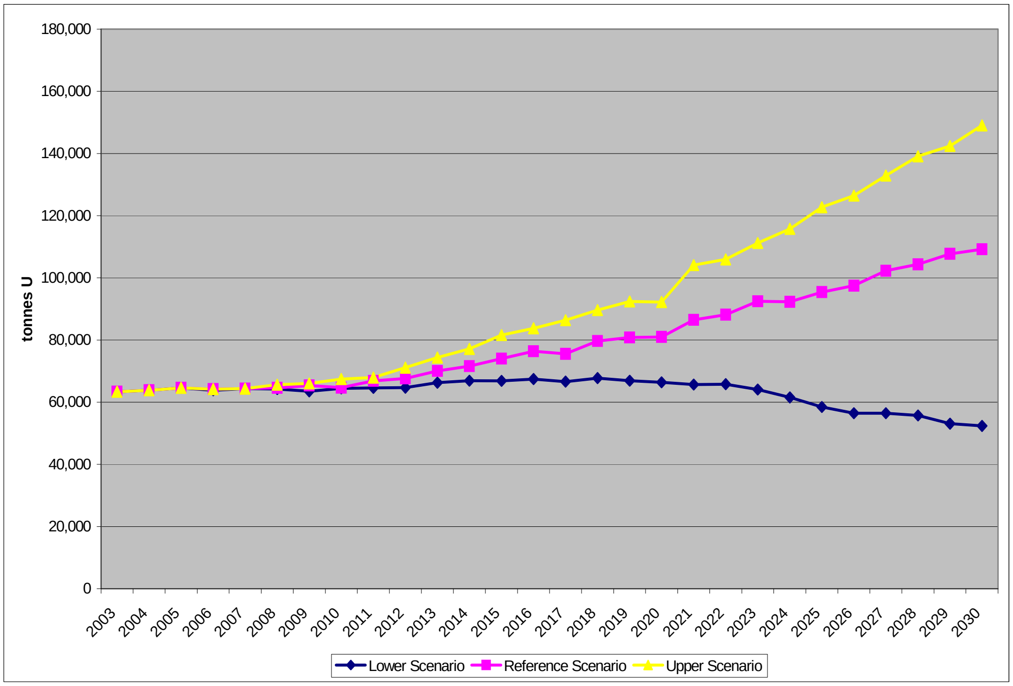


Figure 5: WNA scenarios for world uranium requirements

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 further from the levels of today.

Historical uranium production

Figure 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 than the relationship between supply and demand is very odd and can be explained by there being essentially "four ages of uranium".

- A military era, 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.

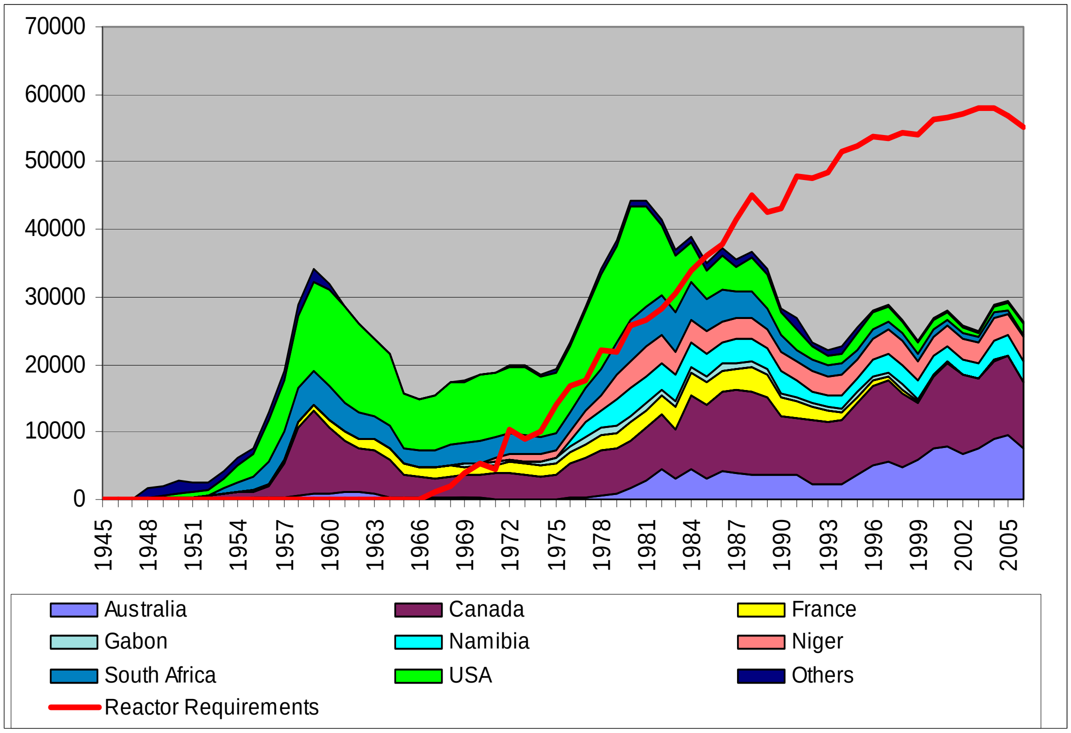


Figure 6: Western world uranium production and demand, tonnes U

- A period 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.

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

- 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.

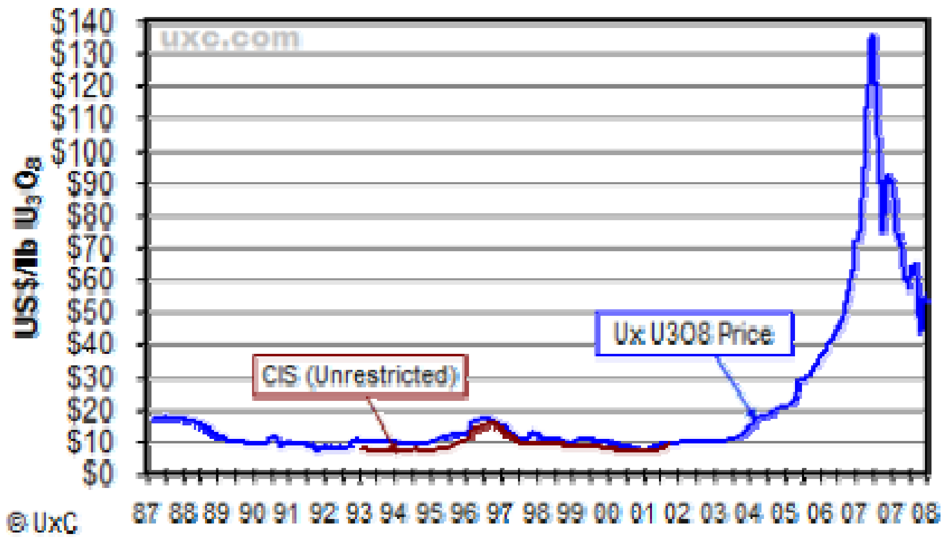


Figure 7: Spot uranium prices

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 "inventory overhang" period led to a long depression in the uranium price, shown in Figure 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 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 the first mine expected to open in Malawi. Plotting future production against the demand scenarios for uranium has to take into account the secondary supplies of uranium and this is shown in Figure 8. Primary uranium production must now rise from around 40,000 tonnes worldwide to 60,000 tonnes in order to

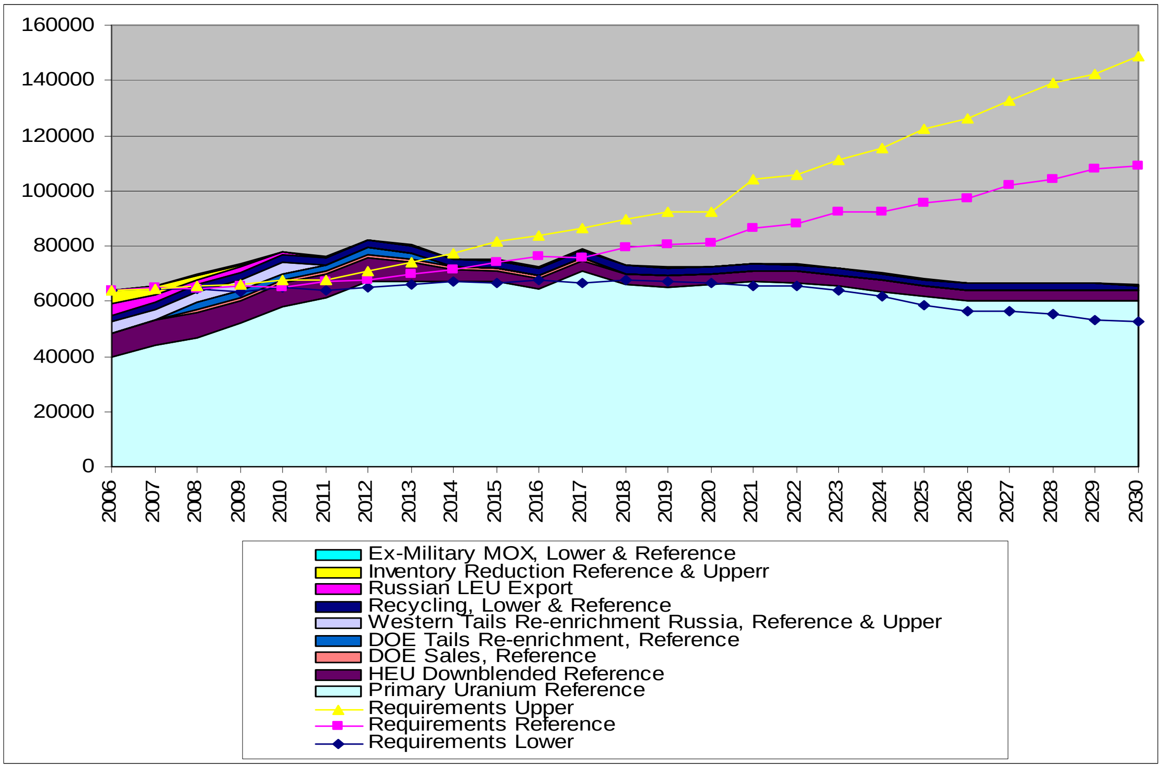


Figure 8: Reference case supply and uranium demand scenarios

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 tonnes 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. The other important feature is the degree of consolidation 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 is 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 orebody, 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 all 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% uranium. The original ore may contain as little as 0.01% uranium. The remainder of the ore, containing most of the

[8] More detail on world uranium mining today is provided in http://www.world-nuclear.org/info/inf23.html
[9] Environmental aspects of uranium mining are discussed at http://www.world-nuclear.org/info/inf25.html

radioactivity and nearly all the rock material, becomes tailings, which are emplaced in engineered facilities near the mine (often in mined out pit). 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 are investigating a fourfold 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 out of the ore by leaching. If there is significant calcium in the orebody (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 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

[10] For more detail on ISL mining, see http://www.world-nuclear.org/info/inf27.html

Secondary supplies still important

Secondary supplies may be defined as all materials other than primary production sourced to satisfy reactor requirements and include inventories, the draw-down of surplus military stockpiles and the use of 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 has not historically been closely related closely to actual reactor fuel requirements, leading to cycles of substantial inventory build-up and then disposal. In particular, there was a substantial build-up of commercial inventories in the late 1970s and early 1980s, when production rose sharply at a time when many reactor projects were getting cancelled. The subsequent run-down 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 has been supplying roughly half of the US nuclear fuel requirements since its commencement in the mid-1990s and has also substantially contributed to important non-proliferation goals. The commercial terms, however, are now judged by the Russians to be non-favourable, as they were signed at a time when they needed hard currency (whereas today they have valuable oil and gas export earnings). They have now announced that there will be no further after the current one expires in 2013. There will, however, be substantial quantities of surplus Russian HEU available for down-

[11] For more details on former military supplies reaching the civil nuclear market, see http://www.world-nuclear.org/info/inf13.html

blending in the period beyond 2013, so it is now reasonable to expect that it will be mostly consumed by internal needs, to fuel 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] Programmes 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. There became little incentive to develop fast breeder reactors, particularly as these present major engineering challenges, which could prove expensive to resolve. Nevertheless, since the late 1970s, around 30% of used fuel arisings from

[12] MOX fuel is described at http://www.world-nuclear.org/info/inf29.html

commercial nuclear reactors outside the former Soviet Union and its satellite states have been covered by 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 programmes 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 programmes 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 only uses part of the potential energy in the fuel, while effectively wasting substantial amounts of useable 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 reprocessing it.

The strong upward movement in uranium prices suggests that utilities owning inventories of reprocessed uranium (RepU) will look once again at utilising these. The greater expense at 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 centre 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 possibly seeking to add to those who 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 annual reactor requirements, with price quotes provided by traders and brokers. Unlike for many other commodities, there is no terminal clearing market place such as the London Metal Exchange (LME) or its equivalents but a market for financially settled futures, involving very small quantities, has been established at NYMEX. In addition, funds have been created to allow investors to directly invest in and hold uranium inventories.

The market has now moved 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 US$10 per pound.

Although there was plenty of industry discussion about this period inevitably ending (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 US$137 per pound in the middle of 2007 but has since slipped back sharply, in a series of stages, to end 2008 at around US$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 imposes a worry that projects will now not go ahead and potential supply shortages could appear in the future (together with another and possibly more dramatic price spike). Everyone knows there is 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 out the interests of both producers and consumers in an equitable way.

This should really not be too difficult, as both uranium producers and reactor investors/operators have similar time horizons, with new projects going through lengthy approval stages then taking several years at the construction stage, before running for 40 years and beyond. The uranium market also has features which suggest that it should not be so volatile and be capable of offering parties proper clear price signals. Most importantly, reactors are generally fuelled only once per year (or longer) so demand is very "lumpy" and not continuous (contrast this with a

[13] Spot prices of uranium are available at http://www.uxc.com

coal-fired generating station). This leads itself to long term contracts, negotiated between buyer and seller, which may last for up to 20 years. These are highly confidential but may reference quoted industry spot prices, while also containing escalation clauses, caps and floors. This has been the traditional way in which nuclear fuel has been sold, with producers using the security of long term contracts as collateral for raising project finance.

Uranium conversion

This enrichment process requires uranium to be in gaseous form and this is achieved by converting it to uranium hexafluoride (UF), which is a 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 programme, which has so far relied heavily on HWRs.

Worldwide, five major suppliers meet the majority of the demand for UF_6 conversion services, namely Cameco in Caneda, 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 satisfy customers. 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% of operating reactors worldwide.[14] The process involves increasing the isotopic level of the uranium-235 contained in natural uranium (0.711%) relative to the level of uranium-238 (99.3%). This majority of nuclear power reactors use low enriched uranium with up to 5% 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% 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

[14] The enrichment stage is outlined in more detail at http://www.world-nuclear.org/info/inf28.html

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 centre.

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 USEC in the United States and Areva in France with more modern and economical centrifuge plants. Even with favourable 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 its capacity with centrifuges derived from a technology-sharing agreement with Urenco, while USEC has decided to develop its American Centrifuge technology, based on DoE programmes in the 1970s and 1980s. Urenco and Areva are also building US 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 may yet turn out to be the technology of the future, as was thought ten years ago when USEC and others were investing significant amounts in laser technology, but its widespread commercialisation (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 a lot of 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% U-235. This will be considered below, but the large quantity (about 1.3 million tonnes worldwide) of depleted uranium (DU) from enrichment plants is also a live issue. Every tonne of natural uranium produced and enriched for use in a nuclear reactor gives about 130 kg of enriched fuel (3.5% or more U-235). The balance is DU (U-238, with 0.25-0.30% U-235). It is stored either as UF_6 or de-converted back to U_3O_8, which is more benign chemically and thus more suited for long-term storage. It is also less toxic. Every year over 50,000 tonnes of depleted uranium join already substantial stockpiles in USA, Europe and Russia.

Some DU is drawn from these stockpiles to dilute high-enriched (>90%) 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 surface and helicopter counterweights, yacht keels, etc, it 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 armour-piercing projectiles, alloyed with about 0.75% titanium. This final use has caused a large amount of controversy, with the allegation that there are risks from radiation 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 the market for fuel becoming increasingly competitive and with several suppliers competing to supply different fuel designs, a trend of continuous fuel design improvements has emerged with continued focus 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 had reorganized at the beginning of this century and has now once again created 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 with its Global Nuclear Fuels partner Hitachi a joint nuclear company.

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 re-licensing projects.

Non-proliferation concerns

A web of licensing, surveillance and national and multinational regulations are in place throughout the nuclear fuel cycle to ensure that safety and non-proliferation objectives are met. This is administered by governments, regional organizations, such as Euratom Supply Agency (ESA) in the European Union (EU), and by the International Atomic Energy Agency (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 in developing nuclear bombs, the expected expansion of nuclear power has brought forth new concerns. [15]

These essentially started with the announcement from North Korea claiming they have an operating centrifuge enrichment programme. There remain substantial doubts about the status of this but this was followed by further revelations from Iran and Libya, showing that they have had similar programmes. 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 programme 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 non-proliferation 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 is timely.

[15] The safeguards regime is outlined at http://www.world-nuclear.org/info/inf12.html

There are a number of ideas, previously floated many years ago, which have been dug out and revamped. One key principle is that the assurance of non-proliferation 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, maybe 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 specialisation 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 programme 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 labour resources.

Nevertheless, it is the case today that provided nations fit in with the obligations imposed by the NPT, international nuclear commerce does not face particularly onerous barriers. 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 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, the 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.

[16] Transport of radioactive materials is highlighted at http://www.world-nuclear.org/info/inf20.html

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 to go ahead with new reactor plans or not. 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 in getting into production.

Within the conversion, enrichment and fuel fabrication sectors, there are interesting market developments happening, 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 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.