sustainable development commission

The role of nuclear power in a low carbon economy

Paper 8:

Uranium resource availability

An evidence-based report for the Sustainable Development Commission
by Future Energy Solutions, an operating division of AEA Technology plc

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Uranium Resource Availability

Produced by Future Energy Solutions for the
Sustainable Development Commission

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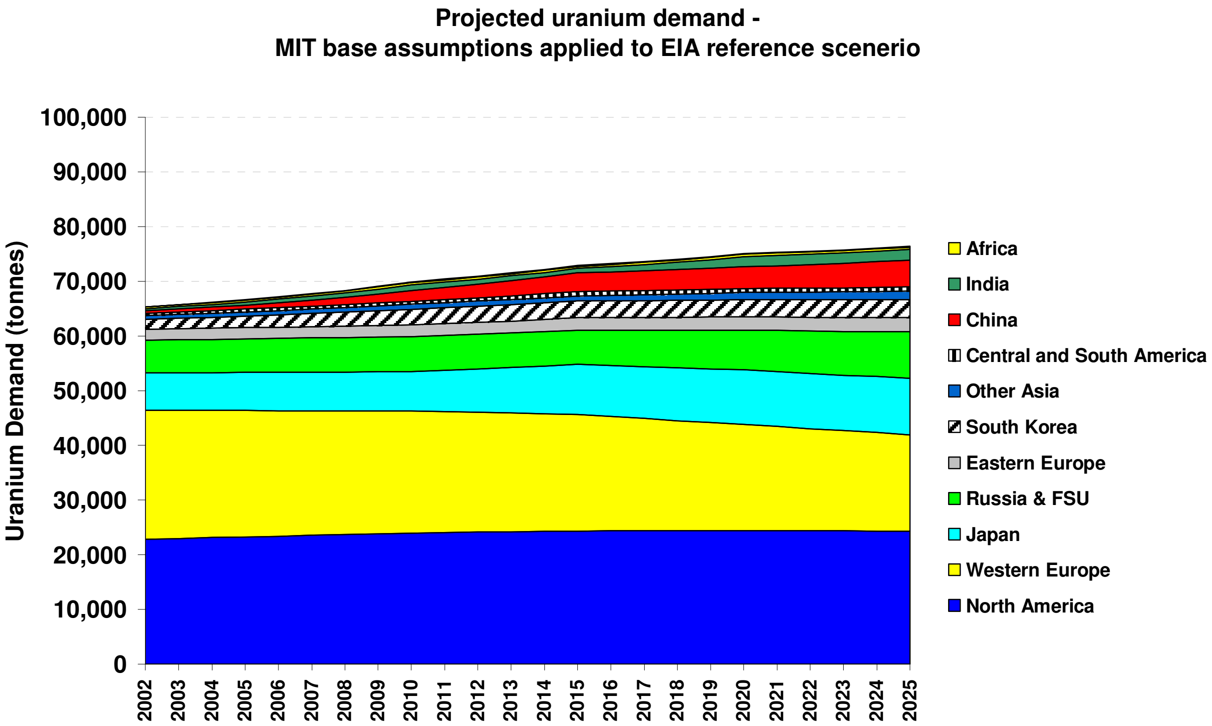
Executive Summary

In recent years, optimism over the future of nuclear power has increased; consequently global uranium demand projections are being revised upward. This shift reflects the new nuclear power capacity that is being planned, particularly for Asia, but also the life extensions that are expected to be granted to many existing power stations across the world.

This report reviews the future availability of uranium resources via an assessment of the demand for uranium from civilian reactors, and of the potential supply of uranium fuel. When considered together, these analyses raise interesting questions related to uranium supply security.

Figure 1

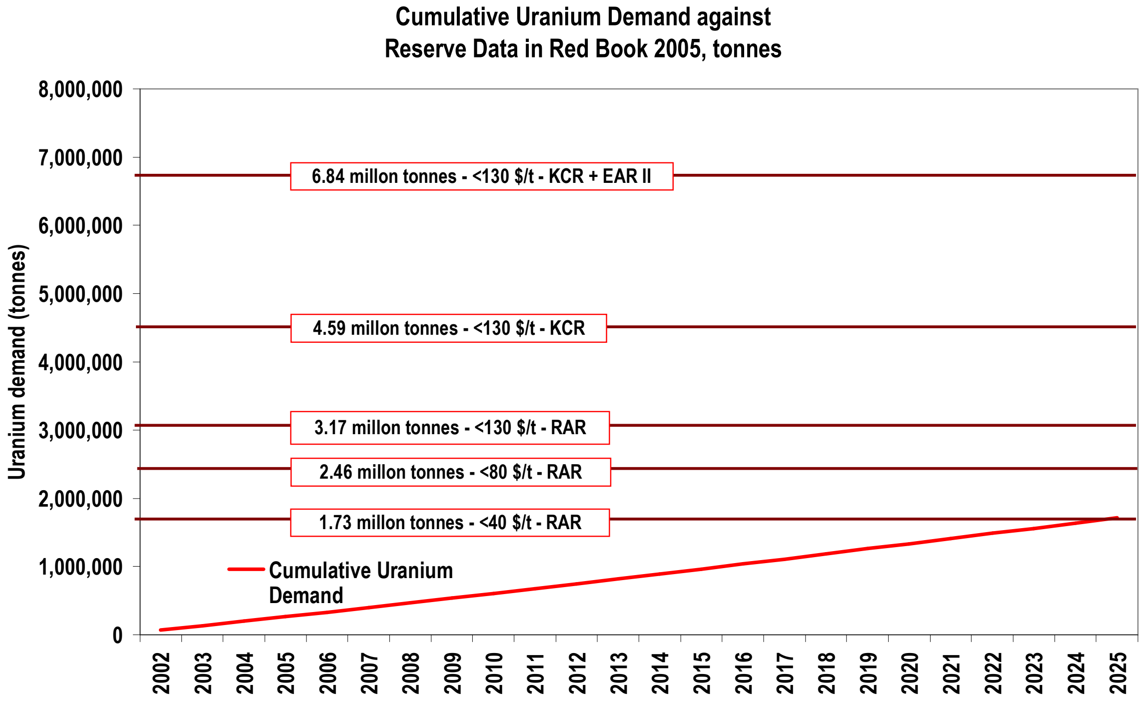


On the demand side, the following key points emerge from the report:

- By 2025, global demand for reactor-based uranium resources is set to increase to 76,000 tonnes – current demand is around 65,000 tonnes (see Figure 1).
- The demand growth is led by Asia – in particular China, India, South Korea and Japan. Demand is expected to fall in Western Europe, despite a recent upward revision of nuclear generating capacity projections for the region. European market share will fall accordingly.
- Growth in nuclear generating capacity is the fundamental driver of growth in uranium demand. In the short term, the utilisation of operating plants has the greater potential to increase demand. Currently, the global average utilisation for nuclear power stations is just over 80% (of the year).

- Other key factors related to the uranium fuel cycle also have significant implications for demand. These can be split into two categories
  - *Parameters related to design characteristics in the power plant* – burn-up and thermal efficiency for example – may reduce demand considerably in the future. However, the contribution to the reduction from better performing new power plants will be small over the next 20 years.
  - *Parameters related to management decisions* have more significance in the short term. Decisions can include for example reducing the amount of uranium-235 in the waste stream from enrichment (tails), this becomes more economic as uranium prices increase. In addition, reducing uranium-235 content in the tails from 0.30% to 0.25% can save 10% of the uranium demand.
- MOX fuel currently only contributes 2-3% of total supply, but this could increase to 5% by 2010. A single-pass MOX fuel cycle can reduce uranium demand for uranium fuel, but this reduction has a theoretical limit of around 16%, excluding existing stocks. This limit is not expected to be reached in the near future.

Figure 2



When placing supply side issues in the context of this demand side analysis, further key points emerge (refer to Figure 2, above).

- Comparing demand projections with current reserve figures, our reference scenario indicates that Reasonably Assured Resources extractable at a cost of less than $40/kg shall be exhausted in 2025. In a further ten years, RAR <$80/kg would also be nearing exhaustion. Given that new plants have a life expectancy of 40 to 60 years, this might be cause for concern.
- However, current reserve data is not suitable for such a direct comparison. Publications of the *Red Book* over the last 20 years have shown an *increase* in reserves over time.

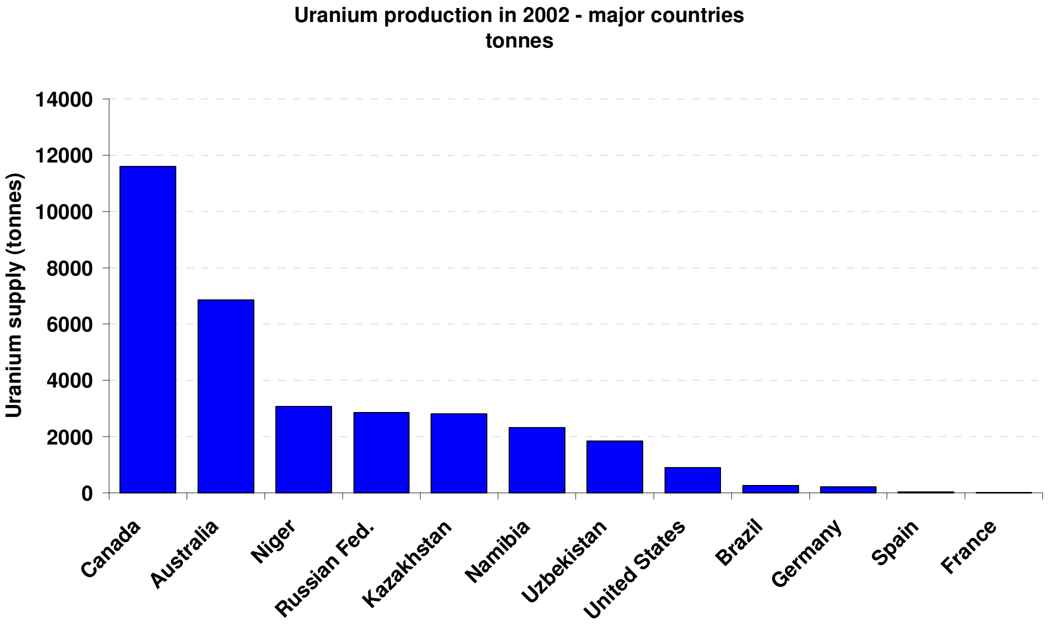
The 1983 publication reports Known Conventional Resources <$80/kg as being 40% below the figure in the 2003 publication. These "new" reserves are the result of investment in research and exploration activities.

- Institutions across the nuclear industry are confident that reserves are sufficient to meet the needs of the next 100 years. While the possibility must exist that further economic reserves do not materialise, on balance their analysis seems reasonable. Even under current reserve data, Known Conventional Resources plus Estimated Additional Resources (II) can be expected to last around 100 years. Speculative resources might extend this period considerably.
- Short term supply needs are of greater concern. A shortfall in supply is widely expected for the next few years. Analysts agree that with significant effort and investment now, disruption to power stations can be avoided. However, there are several uncertain parameters that could exacerbate the shortfall: a rapid increase in utilisation; the end of HEU supplies after 2013; and delays in the introduction of expected production facilities. All of these scenarios are plausible.

There are also many issues relating to the operation of the uranium market and to the geopolitical context of uranium trade. Naturally the geographic distribution of supply and demand is particularly important here. The report focuses on states rather than on uranium firms. Some of the key points are summarised below:

- The uranium market is going through a period of adjustment. Secondary supplies - from inventories built up during the 1970s oil crises and weapons decommissioning – are beginning to run out, but continue to contribute 40% of total supply. Primary production must increase to meet both the decline in secondary supply and increasing demand. The supply response is limited by the high cost of exploration and development of new mines. There is also concern that the uranium price is undervalued – analysts argue that there are signs of serious market failure.

Figure 3



- The EU has little uranium production, but at the enrichment stage is almost self-sufficient (80% is enriched internally). Historically there has been excess capacity in both conversion and enrichment, but there is some concern about the future. The US is increasingly dominant in the conversion market.
- Australia and Canada are the major primary producers (see Figure 3), but Kazakhstan will challenge for the largest producer spot in the next ten years. Russia also makes an important contribution through its unique importance in the secondary supply market. Focus in the uranium market is therefore shifting away from OECD countries. Exacerbated by a tight supply situation, the strategic importance of uranium is increasing for both producer and consumer states.
- EU trade with Australia, Canada and the US is governed by bilateral trade agreements, and there is no indication of difficulties in trade between these countries.

Historically, uranium producers have been located in OECD countries and trade between OECD countries has been unproblematic. The importance of Russia and Kazakhstan in the medium term raises the possibility of additional non-market led strategic behaviour which OECD countries are increasingly aware of.

- Russia and Kazakhstan present strategic challenges.
    - Negotiation with Russia occurs through the EU-Russia Energy Dialogue. EU policy is to restrict the supply of Russian material to a share of 20% of the Community market. However, a tight supply situation, combined with the trade relationships between Russia and several EU accession states, is forcing the EU to review this policy. An important part of Russian supply, the dilution of highly enriched uranium from weapons for use in civilian reactors, is dependent on agreement with the US and is uncertain from 2014.
    - Kazakhstan will play an increasingly important role in the global market. Kazakhstan is generally considered the most successful of "the Stans", and has a positive relationship with OECD countries. There is little immediate prospect of political disruption to the uranium market by the government. Equally, there is no internal unrest which might threaten the industry. While there are some medium term concerns about the internal stability of the country, the outlook is considered positive. The risk of unrest in nearby countries is more serious, and could have implications for investment and for the transport of uranium.

The strategic importance of uranium will increase as demand increases and regionalises; this is raised further by a short to medium term shortfall. Since government influence is significant in the uranium industry, there is an important role for foreign and energy policy in securing trade.

In geopolitical terms, uranium plays a much broader role than simply supplying civilian reactors. Trade patterns are strongly influenced by foreign policy, particularly regarding non-proliferation. The issue is more complicated than allowing uranium to be traded only when it is considered safe to do so; negotiations can arise, as over Iran, where civilian nuclear technology and trade might be offered in return for assurances about enrichment or weapons programmes.

CONTENTS

1 Introduction

The UK Government is conducting a fresh review of energy policy and as a result, nuclear power in the UK is back on the agenda. The *Sustainable Development Commission* (SDC) – the government's independent advisor on sustainable development - wishes to update its position in advance of a formal conclusion of the government's review. To do this SDC is compiling a report summarising the available "evidence" on nuclear power prior to discussion of a revised position. Five broad areas have been identified by SDC for externally conducted research. These are:

1. Economics
2. Waste and Decommissioning
3. Safety and Security
4. Public Perceptions and Community Issues
5. Resource Availability

Future Energy Solutions (FES) has been appointed to undertake the review of *5. Resource Availability.* FES has prepared this report to provide the SDC with a comprehensive overview of the issues surrounding uranium resource availability under a variety of scenarios for the utilisation of nuclear power, and taking into account the geographic distribution of reserves, and the consequences for security of supply. The issue of prices and supply is also covered briefly in the review, with particular emphasis on resource availability.

1.1 Overview

In recent years optimism over the future of nuclear power has increased, and consequently uranium demand projections are being revised upward. This reflects the new nuclear power capacity that is planned, particularly for Asia. It also reflects extension in plant lifetimes that are now expected to be granted for many existing power stations. An increase in the utilisation rates of nuclear plant has increased uranium demand in the US, and the same phenomenon is expected to develop elsewhere.

This report reviews the future availability of uranium resources via an assessment of the demand for uranium at civilian reactors, and the potential supply of uranium fuel. When considered together, these separate analyses raise interesting questions related to uranium supply security. Detailed analysis is restricted to 2025, since projections beyond this point are subject to increasing uncertainty. However, reference is made to the longer term implications for nuclear power.

The analysis is also designed to deconstruct demand and supply into more fundamental components, to illustrate which parameters are significant within the uranium fuel cycle, for example, and what drives them.

Against a background of increasing demand, the importance of securing supply is likely to have increasing political significance. This is particularly so given the level of state intervention in uranium markets and given government interest in the nuclear power (and energy) industry more widely. Issues related to state involvement are raised throughout the report, with particular emphasis on the EU.

We distinguish between availability of resources over the longer term (how much is in the ground) and availability over the short term (how much can be brought to market by a certain time). Implications for the security of supply are different in each case.

1.2 Background

Reactor-related requirements for uranium are fundamentally determined by installed nuclear capacity. In other words, demand is largely driven by the number of power plants that are able to operate. Other important demand parameters are related to the uranium fuel cycle, and are described later in this Chapter.

In the short term, capacity can be projected with some confidence (current installed capacity worldwide is close to 360 GWe), but over the long term, capacity growth could vary significantly depending on growth in electricity demand and the political, social, and market opinion of new nuclear plant.

More flexible over the short term – and still significant over the long term – is utilisation. The utilisation rate is the amount of nuclear energy generated in relation to the total capacity available - worldwide plants currently run at an average of 81% utilisation, this means they run for 81% of the year (or 7,096 hours). A rapid increase in utilisation might have a significant impact on demand – and on the availability of resources over the short term.

The rest of this introduction is divided into two sections. In the first, we present a brief explanation of uranium markets over the last 50 years; uranium is an unusual commodity and this is reflected in the operation of the market. This is intended to provide a useful context in which to view the uranium analysis in subsequent chapters.

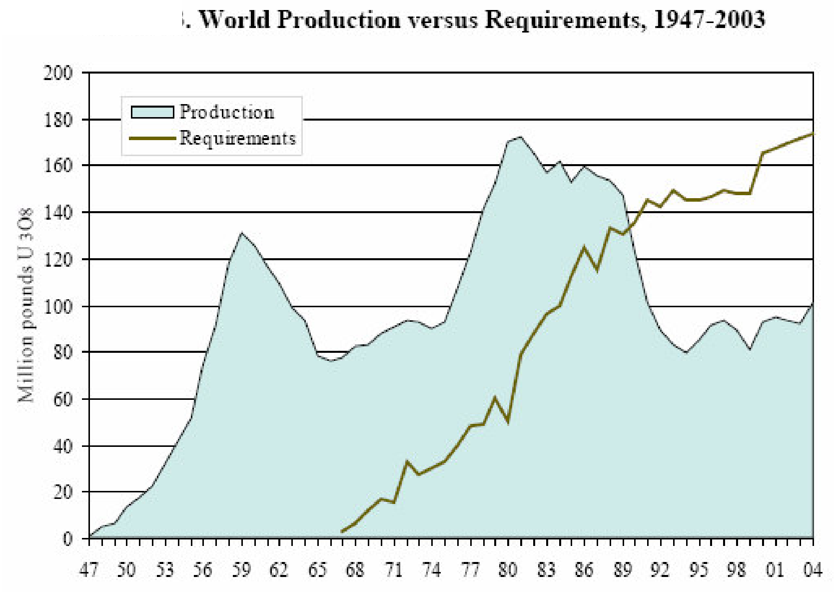
In the second section, a concise nuclear fuel primer is provided; this is intended to prepare the reader for some of the more technical aspects in the following chapters, particularly those related to the uranium fuel cycle. Readers may wish to refer back to the primer while they read later sections of the report.

1.3 Uranium Markets – A History

The uranium market is unique in that production has been out of synch with civilian reactor requirements since significant demand for uranium first developed in the 1940s (see Figure 4).

On the production side, the first peak in the late 1950s was the consequence of military-related demand. The second peak in the late 1970s was the result of stockpiling following the oil price crises. By the end of the 1970s, both production and exploration for uranium dropped dramatically; the market price subsequently crashed in response to a considerable oversupply.

Figure 4



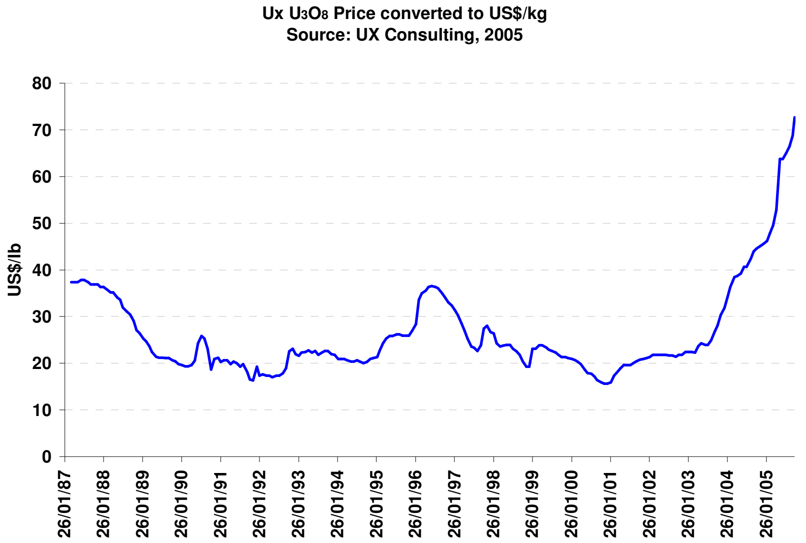
. World Production versus Requirements, 1947-2003

Source: Combs, 2004[1]

During the 1970s, quoted prices climbed to US$ 40/lb, this is the equivalent of about US$90/kg, but then since fell to lows of less than US$ 20/kg by 1990s. Prices have recently averaged more than US$ 60-65/kg, and recently climbed to more than US$ 70/kg in October 2005 (Figure 5). In real terms, this is the highest level since the early 1980s, and it is still climbing.

Prices are given for uranium oxide concentrate (U_3O_8), which is also known as yellowcake. Yellowcake is produced at the conversion stage of the uranium fuel cycle, as described below. Prices are usually given in imperial measurements, however, for the remainder of this report price information is provided in US$/kg.

Figure 5



Ux U_3O_8 Price converted to US$/kg
Source: UX Consulting, 2005

Source: UXC, 2005[2]

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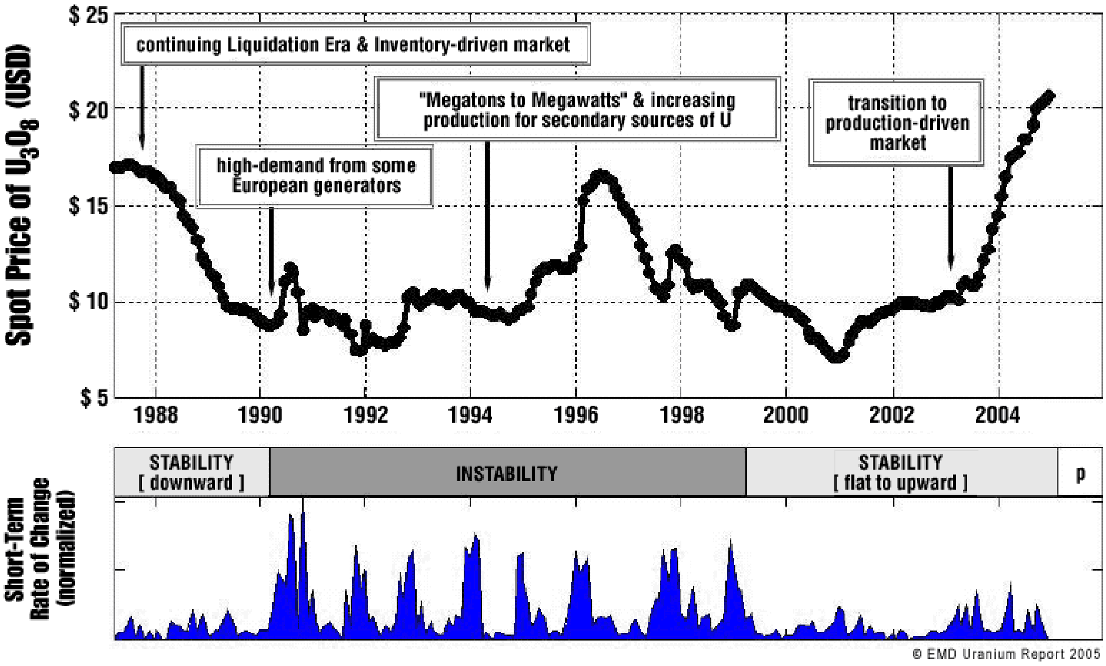
[1] "Fueling the Future, A New Paradigm - Assuring Uranium Supplies in an Abnormal Market", Combs J, *WNA* (Sep 2004), http://www.world-nuclear.org/sym/2004/pdf/combs.pdf

Price volatility has also changed over time. Figure 6 displays a range of interesting information. The top half describes price information as above, but with descriptions of changes to the market.

In the 1980s, the market was driven by liquidation of government and commercial stocks. The *Megatons to Megawatts* programme refers to a 1993 agreement between the US and Russia. This is an agreement to convert *highly enriched uranium* (HEU) taken from dismantled Russian and American nuclear warheads into *low-enriched uranium* (LEU) fuel which is suitable for civilian reactors. The future of this agreement after 2013 (known as *HEU-II*) is currently uncertain.

Figure 6



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As seen in the bottom section of Figure 6, throughout the 1990s price instability was very high, partly as a result of uncertainty over the HEU programme and other government led activity (for example, there was limited transparency over the amount and timing during a period of inventory liquidation).

In general, the release of "secondary supplies" has been disruptive in the market since the 1980s. Secondary supplies are those that do not come through the supply chain directly from uranium ore. These include HEU; state and commercial inventories; and reprocessed fuel.

Reprocessing involves the removal of plutonium from reactor waste so that it can be "burned" alongside uranium in the reactor core (it is also possible to reprocess uranium from the waste, but this is less economically viable).

Secondary supplies are falling in relation to supply from primary production as inventories and HEU begin to run out and demand begins to climb. Primary production is expected to dominate supply by 2020. As Figure 6 suggests, the latest phase is a transition to this

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[2] Historical Ux Month-end Spot Prices, *UX Consulting* (2005), http://www.uxc.com/review/uxc_prices_mth-end.html

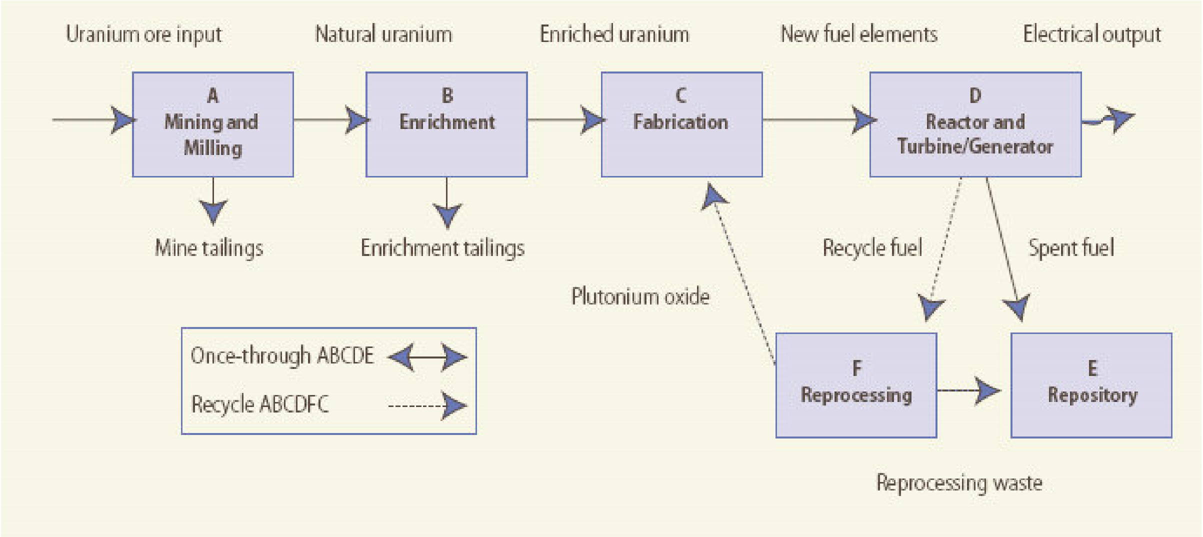
primary production-driven market. However, secondary supply continues to contribute around 40% of global supply at present.

1.4 Nuclear Fuel Primer

Calculations of uranium demand and uranium supply are complicated, involving a number of interrelated factors. This section explains the basic concepts of the uranium fuel cycle – from ore to waste – and describes the most significant parameters that will be used in the analysis. The fuel cycle methodology used in this report is derived from the major Massachusetts Institute of Technology (MIT) report *The Future of Nuclear Power*, which was published in 2003. The formulae behind the modelling in this report can be found in Appendix 1 of the MIT report.[3]

Figure 7 (MIT) provides a high level overview of the key stages in the uranium fuel cycle. Each category is described below.

Figure 7



1.5 Mining and Milling

Uranium is a relatively common element, occurring in most rocks in concentrations of 2 to 4 parts per million. It is as common in the earth's crust as tin, tungsten and molybdenum.[4]

The concentration of uranium in ore can vary by several orders of magnitude. Reserves with the highest concentration (which accordingly tend to be more economic) are found predominantly in Australia and Canada. The Saskatchewan mine in Canada has ore grades 100 times the global average according to its owner, Cameco.

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[3] "The Future of Nuclear Power", *MIT* (2003) http://web.mit.edu/nuclearpower/

[4] "What is Uranium? How does it work?", *Uranium Information Centre, UIC* (2005) http://www.uic.com.au/uran.htm

Milling occurs either on site or very close to uranium mining, since transportation of a large volume of rock is uneconomic. At the mill the ore is crushed and ground to a fine slurry which is leached in sulphuric acid to allow the separation of uranium from the waste rock. It is then recovered from solution and precipitated as uranium oxide (U_30_8 or often denoted as U3O8) concentrate – this is commonly known as yellowcake.

1.6 Conversion

Because uranium needs to be in the form of a gas before it can be enriched, the U_30_8 is converted into the gas *uranium hexafluoride* (UF_6) at a conversion plant in Europe, Russia or North America. Movement of yellowcake to the conversion plant is the first significant transportation requirement of the supply chain.

1.7 Enrichment

The natural proportion of the Uranium-235 isotope in U_30_8 is just 0.71% - the remainder being the Uranium-238 isotope. The vast majority of all nuclear power reactors in operation and under construction require "enriched" uranium fuel in which the proportion of the U-235 isotope has been raised from 0.71% to about 3.5%. The precise level of enrichment required is determined by the reactor design (see below).

The enrichment process removes about 85% of the Uranium-238 by separating the gaseous uranium hexafluoride into two streams:

1. one stream is enriched to the required level and then passes to the next stage of the fuel cycle
2. the other stream is depleted in U-235 and is called "tails". It is mostly U-238.

Tails usually contain only 0.25% to 0.35% U-235. The exact percentage can be altered by management of the enrichment process, and is ultimately an economic decision. When the uranium hexafluoride fuel (from conversion plant) is cheap, it is more profitable to increase the throughput of the fuel and reduce the amount of enrichment that takes place. In this scenario a greater amount of U-235 remains in the tails.

When uranium is expensive, the process of enrichment becomes more economic – enrichment work increases and the input of uranium feedstock declines. The tails figure will also decline, reflecting the improved capture of U-235.

As a result of this trade-off, enrichment strategies can have a significant impact on uranium demand. Utilities may choose to extend the life of the fuel they are contracted for when the fuel is expensive – assuming there is available enrichment capacity. High uranium prices can therefore result in a reduction of uranium demand per unit of electricity produced.

The first enrichment plants were built in the USA and used the gaseous diffusion process, but more modern plants in Europe and Russia use the centrifuge process. This has the advantage of using much less power per unit of enrichment and can be built in smaller, more economic units.

1.8 Fabrication

Enriched UF_6 is transported to a fuel fabrication plant where it is converted to uranium dioxide (UO_2) powder and pressed into small pellets. These pellets are inserted into thin tubes, usually of a zirconium alloy or stainless steel, to form fuel rods. The rods are then sealed and assembled in clusters to form fuel assemblies for use in the core of the nuclear reactor. This stage is not required for the fuel cycle calculations in this report.

1.9 The Reactor and Turbine Generator

Two characteristics of the reactor and turbine are particularly significant for our analysis.

Burn-up

Burn-up is a measure of thermal energy released by nuclear fuel relative to its mass, measured in gigawatt days per tonne (GWd/t). Increasing the burn-up of the fuel leads to a reduction in the quantity of fuel used for a given amount of electricity produced. In effect, the uranium resource is used more efficiently by the reactor.

Burn-up is a design characteristic of the reactor. As reactor design improves, higher burn-up reactors may therefore be able to reduce global demand in the future. It is around 50 GWd/t in modern *Light Water Reactors* or LWRs which include the AP1000 and EPW reactors most likely to be considered in a new UK programme. LWRs represent nearly 90% of global capacity.

However, burn-up also determines the exact level of enrichment needed (see "*enrichment*"). At a burn-up of 35 GWd/t (typical of early LWR), fuel must be enriched to 3.2%. At 50 GWd/t, fuel must be enriched to 4.5%, according to the MIT formulae. This increases demand for uranium at the enrichment stage of the fuel cycle.

Consequently, the demand for higher enriched fuel for increased burn-up can actually increase overall demand for uranium if other design characteristics are held constant.

A small number of reactors, notably the Canadian CANDU and early British AGR gas-cooled reactors, do not require uranium to be enriched. Without the trade off with enrichment, the burn-up in such reactors leads to uranium demand *reduction* as the fuel is used more effectively.

Future reactor developments may also have the potential to increase burn-up significantly. Over the next two decades, however, LWR will continue to dominate the global fleet of reactors – so lower burn-up technologies are likely to have a limited impact on demand over this time-frame.

Thermal efficiency

Nuclear power plants generally use the thermal energy produced by the nuclear reaction to produce steam to drive a turbine. Some designs use a gas turbine instead. The thermal efficiency is the electrical output of the plant divided by thermal input. In current LWRs, this is typically around 33%. However, some future reactor designs promise thermal efficiencies of 50% and higher.

1.10 MOX Reprocessing

Spent fuel discharged from light-water reactors contains appreciable quantities of fissile (U-235, Pu-239), fertile (U-238), and other radioactive materials. These fissile and fertile materials can be chemically separated and recovered from the spent fuel. The recovered uranium and plutonium can, if economic and institutional conditions permit, be recycled for use as nuclear fuel.

Mixed oxide fuel, or MOX, currently powers the equivalent of just 2% of total nuclear capacity, but is expected to make a more significant contribution in the future[5].

Plutonium, as an oxide, is mixed with depleted uranium left over from an enrichment plant to form fresh mixed oxide fuel (MOX, which is UO_2+PuO_2). MOX fuel, consisting of about 7% plutonium mixed with depleted uranium, is equivalent to uranium oxide fuel enriched to about 4.5% U-235 (assuming that the plutonium has about 60-65% Pu-239). If weapons-grade plutonium were used (>90% Pu-239), only about 5% Pu would be needed in the mix.

In a "single pass" MOX fuel system, all of the material from the "normal" fuel - uranium oxide (UOX) - is recycled once, and none of the MOX fuel is recycled. Although more than one pass of the MOX is possible, the number of recycles possible using current reprocessing and reactor technology is limited by:

a) the build-up of plutonium isotopes that are not fissionable by the thermal neutron spectrum found in light-water reactors and
b) the build-up of undesirable elements, especially curium.

The MOX calculations in this report thus assume a "single pass".

MOX can be seen as a tool for non-proliferation, since plutonium taken from thousands of weapons has already been "burnt" in reactors – in fact MOX has become the key mechanism for disposal of weapons-grade plutonium (>90% Pu-239) by the US and Russia.

However, MIT argue that "separated plutonium is especially attractive for theft or diversion and is fairly easily convertible to weapons use, including by those sub-national groups that have significant technical and financial resources". MOX could therefore pose a risk of proliferation, particularly in countries less able to provide security for nuclear plant and the supply chain.

In the single pass scenario, the demand reduction of MOX is limited to 16%. This limit exists because MOX fuel is produced from UOX reactor "waste" (uranium oxide, or UOX, is the fuel used in "normal" reactors). More waste would be required to feed more MOX reprocessing – which means more UOX reactors would be required. Beyond 16% there is no extra waste fuel to reprocess. In the short term there is a supply of historical nuclear waste available, as well as contribution from HEU (see Chapter 2 - Demand).

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[5] Information and Issue Briefs – "Mixed Oxide Fuel", *WNA* (Jul 2003), http://world-nuclear.org/info/inf29.htm

2 Demand

2.1 Introduction to Demand

This section covers the demand side aspects of uranium markets, focusing on uranium fuel demand from civil nuclear power generation trends for the period up to 2025. According to the OECD Nuclear Energy Agency[6]:

> "Reactor-related requirements for uranium…are fundamentally determined by installed nuclear capacity, or more specifically by the kilowatt-hours of electricity generated… Other factors that affect…uranium requirements include plant efficiency; fuel-cycle length and discharge burn-up; and the ratio between natural uranium and enrichment prices."

In the short term, uranium demand is dictated primarily by the utilisation rates of existing generating capacity, as well as other technical characteristics of that capacity such as power conversion efficiency and fuel burn rates.

In the medium to long term, trends in the generating capacity of nuclear plant worldwide (accounting for decommissioning, extensions and additions) and the evolution in new reactor designs become increasingly significant.

With operating nuclear capacity being a key determinant of uranium demand, this Chapter;

- compares published projections of regional and global nuclear generating capacity, and
- defines the key parameters that affect the demand for uranium from the world's reactors.

Further analysis is done on a plausible base case projection for power capacity. Sensitivities are then applied based on those operating and technical assumptions that are variable. This enables a range of possible demand scenarios to be investigated. The potential for a higher capacity growth scenario than the reference is also referred to where appropriate.

Our approach to determining uranium fuel demand applies a series of standard parameters determined by MIT, which has undertaken considerable independent research into the nuclear fuel cycle from ore to waste; the technical assumptions made on the fuel cycle are defined later in the chapter. By applying these factors to the base case capacity growth scenario, we are able to estimate the demand for uranium fuel, the basic approach is as follows:

[Capacity GWe] x [Current Regional Utilisation %] ÷ [Efficiency 33%] x [Fuel Factor] = [U Demand]

To support the demand side analysis, an alternative top-down approach is taken to act as a cross check and ensure the output figures are broadly in agreement.

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[6] "Uranium 2003: Resources, Production and Demand", *OECD Nuclear Energy Agency* and the *International Atomic Energy Agency* (2004)

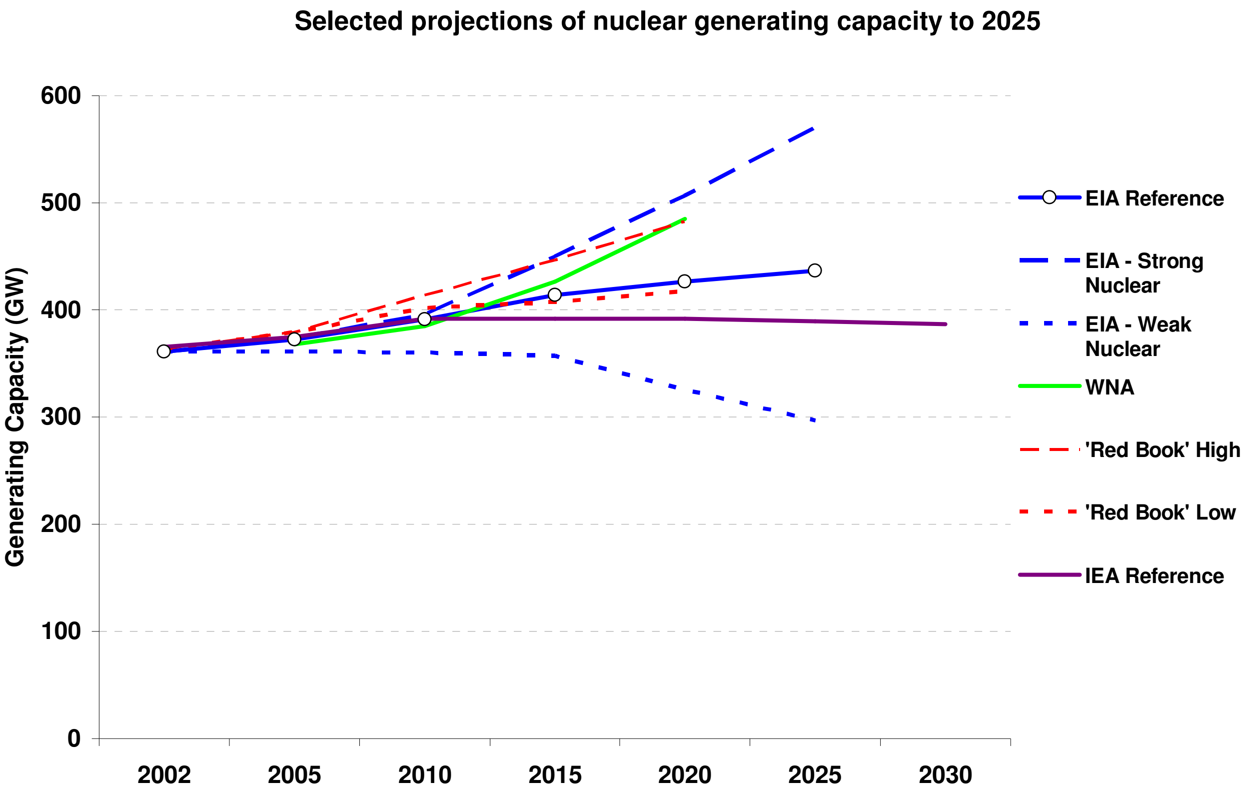
Using 2004 published electricity generation data (in GWh) and uranium demand data (tonnes), uranium demand per unit of electricity output is calculated. This can be done either globally or nationally. By dividing the known GWh output and known operating capacity of a country's nuclear power (GWe), we can calculate the annual average utilisation in hours (h) or a percentage (of the year).

While it may be possible to get agreement on a global level, disaggregating down to regional level may, in a few cases, produce different results; this is explained in more detail later in the chapter.

2.2 Capacity Projections

Figure 8 shows selected projections of nuclear generating capacity in GWe to 2025 of which we have selected the *EIA Reference* as the base case. In most cases, any interim year data points are interpolated where such data is not provided.

Figure 8



Each projection shown in Figure 8 is selected because it is considered to be from an authoritative source, and in most cases, because it provides sufficient detail to determine the assumptions that are specific to nuclear power generation:

- *The* ***US Energy Information Administration (EIA)***[7] *is a widely used source of electricity projections. In 2005, it has for the first time focused its three latest electricity projections on the nuclear contribution: "weak nuclear power"; "strong nuclear power revival" and a reference scenario. Projections of world nuclear energy consumption are derived from nuclear power electricity generation projections from EIA's International Nuclear Model (INM).*

- *The* ***"Red Book"[8] (2004)****, published jointly by the* ***OECD Nuclear Energy Agency (NEA)*** *and the* ***International Atomic Energy Agency (IAEA),*** *is the industry standard for data on the supply of uranium, but also contains generating capacity data. This publication analyses the uranium supply and demand situation throughout the world by evaluating data on uranium resources, past and present production, and plans for future production. This Red Book is prepared on the basis of data obtained through questionnaires sent by the NEA to its member countries (18 countries responded) and by the IAEA for those states that are not OECD member countries (25 countries responded). The sister publication the "Brown Book 2005" contains official information provided by governments of OECD member countries, including quantitative data and short narrative reports that give the status of current nuclear energy programmes, trends and issues in their respective countries along with projections up to 2025.*

- *The* ***World Nuclear Association (WNA)***[9] *publishes data on its website on current capacity and new plant in the pipeline, from which the curve is derived using assumptions about the typical time from plan to operation. The WNA draws much of its information and data from its members which consist of 127 members made up of largely nuclear power utilities, uranium mining companies, nuclear fuel producers, and atomic research establishments. Other sources of information and data are derived from a wide range of sources, including nuclear engineering journals, the OECD NEA, and the US Department of Energy.*

- *The reference scenario from the* ***International Energy Agency (IEA)***[10] *is also included, since the IEA is often used as a source for electricity projections. IEA data and information is gathered from IEA member states, and the primary source being relevant government body in energy matters, for example, the UK Department of Trade and Industry (DTI). The UK DTI in turn obtain data from surveys and submissions from industry and their respective associations.*

Based on the result from Figure 8, several broad observations can be made:

- Firstly and unsurprisingly, there is a general consensus on current installed capacity levels for the period 2002 to 2005.

- By 2010, there continues to be broad agreement, with only 10% difference between the lowest and highest of these projections. Again this is unsurprising given that known existing capacity will strongly influence this figure.

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[7] "International Energy Outlook", *US Energy Information Administration* (Jul 2005), http://www.eia.doe.gov/oiaf/ieo/index.html

[8] "Nuclear Energy Data 2003", *NEA/OECD* (2004)

[9] Information and Issue Briefs – "World Nuclear Power Reactors 2004-05 and Uranium Requirements", *WNA* (Sep 2005), http://www.world-nuclear.org/info/reactors.htm

[10] "World Energy Outlook 2004", *International Energy Agency* (2004)

- The lines begin to diverge after 2010, as different assumptions are made – for example, about the likelihood of additional and replacement capacity, as well as dates for decommissioning. Such uncertainties result in a highest figure (*EIA strong nuclear*) nearly twice that of the lowest by 2025 (*EIA weak nuclear*). Only one projection suggests a significant reduction in capacity over the period.

As we look in detail, we see fairly strong agreement between two particular sources, the EIA and *Red Book*. In both sources:

- the *EIA Strong Nuclear Revival* closely matches the *NEA/IAEA Red Book high scenarios,* while

- the *EIA reference* scenario is close to the *Red Book Low scenario.*

The *WNA* projection (which is derived from planned and proposed nuclear plants only, and not based on energy demand projections) shows low growth after 2010, but then reaches the *Red Book High* level by 2020. Differences between the two prior to 2025 may be the result of assumptions in the timing of plant introduction applied in our analysis.

At the time of writing this report, the IEA have yet to publish their latest projection, but based on the latest publication (2004) it steers a more pessimistic trend suggesting a smaller role for nuclear power in the future global power mix.

By 2015, the *EIA reference* projection shows capacity at some 11% higher than the equivalent *IEA reference* projection. However, the EIA notes that it has increased its 2025 reference scenario figure by 13% since the 2004 publication. The 2005 edition of the *World Energy Outlook* by IEA (due in November 2005) is likely to increase its projections.

The EIA and IEA are effective forecasters since both organisations take a multifuel approach, and so forecasting nuclear power in the context of competing fuels and national policies. Based on these factors, these two sources are favoured, although we do not ignore the evidence provided by the nuclear industry.

Both the EIA and IEA use parameters such as economic growth and energy intensity to estimate energy requirements at the national level, including total electricity demand and total generating capacity. The nuclear share of these totals is derived from a combination of the existing share; the "expected" addition or retirement of power stations (largely from stated policy objectives and expert opinion since, as the EIA argues, "in very few cases is the decision to build new nuclear plant based solely on economics"); the likely impact of other fuel prices on the position of nuclear power within each electricity market (which will largely determine the utilisation rate); and other considerations such as environmental (greenhouse gas abatement) policy.

The EIA provide a detailed and explicit reference to the issues affecting nuclear power as published in the *International Energy Outlook 2005*. In addition, EIA publish three discrete scenarios which are related to different nuclear power growth rates, while IEA does not provide such scenarios.

Based on the evidence and detail provided by the EIA, the *EIA reference scenario* is selected as the base case capacity projection for this report.

2.3 EIA Capacity Growth Assumptions

It is noted above that the EIA has raised its forecast for nuclear generation in 2025 by 13%. This is a consequence of:

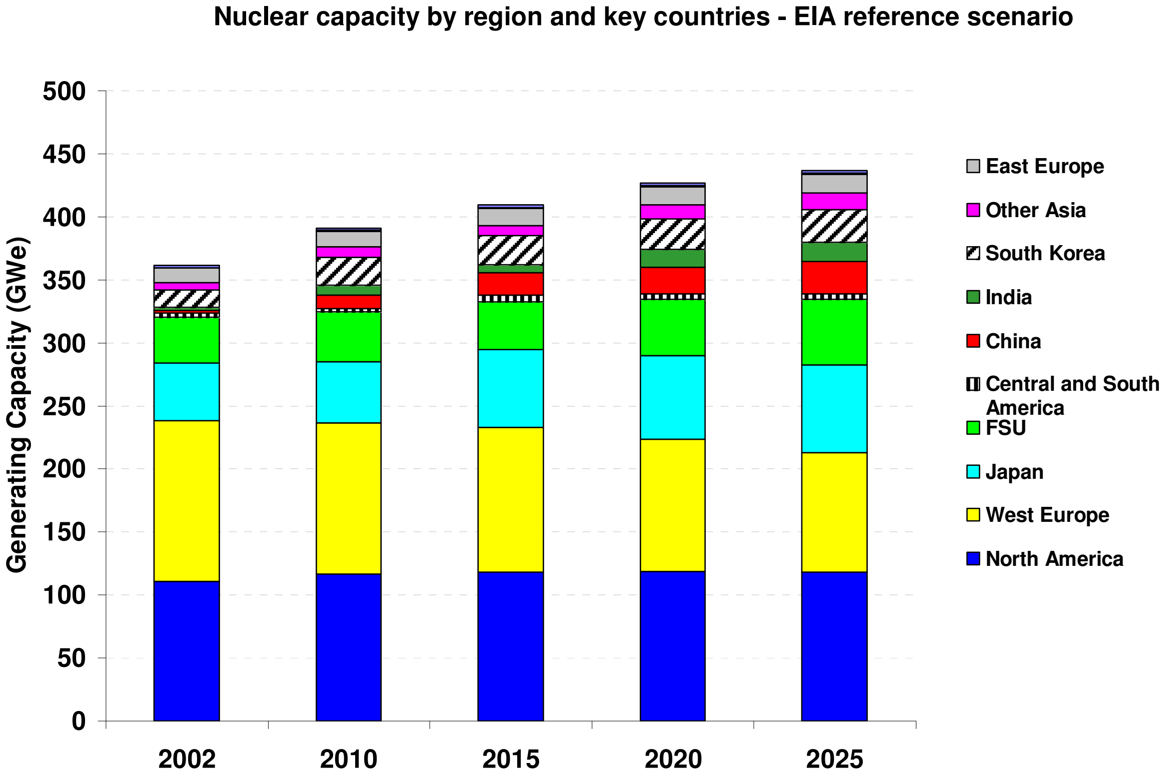
- increased utilisation rates
- the expectation of plant-life extension in mature nuclear countries
- higher fossil fuel prices and
- the entrance into force of the Kyoto Protocol.

The following quote is part of the description of its nuclear scenarios on pages 72 and 73 of the EIA report:

> *"Two opposing scenarios of nuclear power development can be used to assess the potential of nuclear power in the electricity markets of the future.*
>
> *In a "strong nuclear power revival" case developed for 2005, few nuclear plants are retired, and new builds increase the world's total nuclear generating capacity to 570 gigawatts in 2025.*
>
> *In contrast, a "weak nuclear power" case assumes that nuclear power programs, especially in Western Europe and the EE/FSU, are dismantled, few new nuclear power plants are constructed, and installed nuclear power capacity falls to 297 gigawatts in 2025. The reference case projects an increase in world nuclear capacity, from 361 gigawatts in 2002 to 422 gigawatts in 2025.*
>
> *Much of the expansion in nuclear generating capacity projected in the strong nuclear power revival case—a total of 148 gigawatts—is in regions with older, more mature nuclear power markets. Many Western European and EE/FSU countries have established nuclear power industries, and they would be capable of staving off the decline in nuclear power capacity projected in the reference case by reversing planned phase outs of existing nuclear power plants, lengthening operating lives, and constructing new nuclear capacity in response to, for example, concerns about climate change."*

The *EIA reference scenario* is a plausible projection between the extremes of the "nuclear revival" and the "weak nuclear" projections – and hence best suited to an impartial analysis. The regional distribution of nuclear generating capacity under the reference scenario is depicted in Figure 9.

Figure 9



2.4 Regional Capacity Forecast Summary

- The *EIA reference scenario* therefore projects an overall expansion of capacity from about 360 GWe in 2002 to 435 GWe in 2025 (an increase of 17%).

- Western Europe begins to contract after 2015, but continues to hold 95 GWe capacity by 2025.

- North America remains stable at around 120 GWe throughout the forecast period.

- Several mature nuclear power countries, such as those within the Former Soviet Republics (FSU), Japan and South Korea, experience strong growth over the period. For example, Japan nearly doubles its capacity, moving from 46 GWe up to 70 GWe.

- Rapid growth is also experienced in less established nuclear power countries, in particular India and China. India moves from 3 to 15 GWe capacity by 2025, and China from 2 to 26 by 2025. Interestingly the Chinese figure is significantly lower than the official policy target of 36 GWe by 2020. This may reflect the opinion – reported in an IAEA paper by the Deputy Director of the Institute of Nuclear and New Energy Technologies in Beijing – that since priority has been given to other generating options, especially hydropower and coal, funding limitations are a strong barrier to meeting the nuclear target.[11]

- Although the EIA does not state each country separately for the region "Other Asia", we infer the growth to occur in countries in Indonesia, Pakistan, Vietnam and North Korea based on evidence provided by planned and proposed capacity data published by the WNA.

- Since market share for Western Europe reduces over the period, the EU's ability to influence markets is likely to decline.

2.5 Projecting Uranium Demand

Although the capacity of nuclear power is a fundamental driver for uranium demand, a number of other factors have a significant impact on the relationship between the two. Of particular importance is the **utilisation of capacity**; in this report, we define utilisation as the period of the year that the power capacity is operating (this is expressed in either hours or as a percentage).

The utilisation rate is one of several demand side sensitivities presented at the end of this Chapter. However, a series of other calculations are needed in order to derive uranium demand from nuclear generating capacity.

To make this conversion, this Chapter follows the fuel cycle methodology outlined in Chapter 4 of the MIT report, *The Future of Nuclear Power*[12]. This approach has the advantage of clearly demonstrating the assumptions and parameters required for making detailed uranium demand calculations. By breaking down the calculations into relevant components, the approach facilitates the sensitivity testing of a number of parameters which may improve our understanding of the various factors that can affect future uranium demand (see Chapter 3 - Supply).

One set of parameters must be included to take into account the passage of uranium fuel through a nuclear reactor. The key parameters include:

- the amount of **thermal energy produced per unit mass of fuel** (called the *fuel burn-up*) and
- the **thermal efficiency** of the plant.

The two parameters differ in that fuel burn up reflects the efficient use of U-235 by the reactor to produce thermal energy - while the thermal efficiency indicates the electrical generation possible given a unit of thermal energy. These parameters calculate the amount of uranium fuel required given a particular capacity and utilisation rate.

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[11] Bulletin 46/1 – "China's Challenging Fast Track", Zhihong W, *IAEA* (Jul 2004), http://www.iaea.org/Publications/Magazines/Bulletin/Bull461/article6.pdf

[12] "The Future of Nuclear Power", *MIT* (2003), http://web.mit.edu/nuclearpower/

2.6 Uranium Tails

Chapter 1 - Introduction introduces the enrichment process and the composition of the waste product known as **tails**. This waste stream contains about a tenth of the U-235 found in enriched uranium, typically ranging from 0.25% to 0.35%.

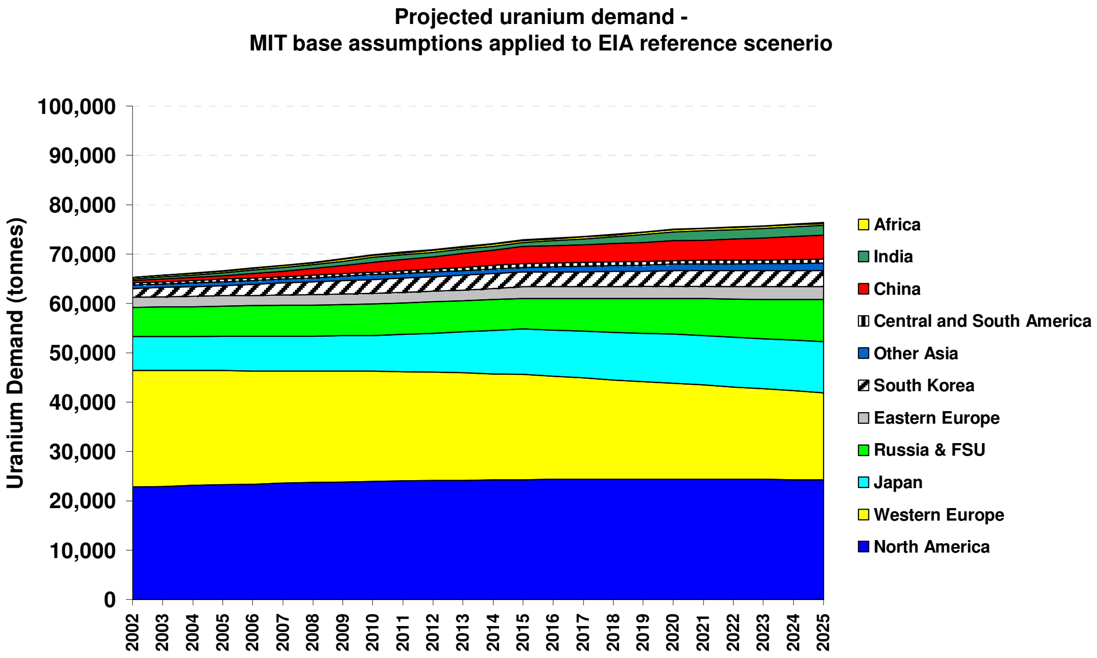
When uranium prices are low, it is possible to create the same fuel product by using a high UF_6 feedstock and low enrichment (which is in itself expensive); alternatively, when uranium prices are high, it may be economic to throughput less UF_6 and increase enrichment. In the former, case less uranium is "stripped" from the tail, resulting in a higher concentration of U-235 in the tail (the tails assay increases towards 0.35%). Consequently, with greater U-235 "waste" in the tails, low uranium prices can increase the throughput and hence overall demand for uranium.

The *re-enrichment* of tails is also possible, and is also governed by economics. Russia, using technology previously employed in weapons programmes, now uses some of its excess enrichment capacity to re-enrich tails. Since this is a secondary supply source of uranium, it is included in Chapter 3 - Supply.

2.7 Demand Forecast by Region

Adopting assumptions for each of the above fuel cycle parameters and applying them to the *EIA reference scenario* produces a forecast profile as seen in Figure 10. In this case utilisation rates have been fixed at their region specific level, calculated using the latest 2004 data provided by the *WNA*.

Figure 10



Given the increase in generating capacity in the *EIA reference scenario* it is not surprising that uranium demand also increases over the period by roughly the same order of magnitude moving up 15% to about 76,000 tonnes – current demand is around 65,000 tonnes.

The *NEA/IAEA Red Book* is the only source that provides direct estimates of uranium demand to 2020. By this time, it estimates that annual demand will have reached 73,500 tonnes under its *low scenario*. This compares to a value of 75,000 tonnes under the analysis above; a difference of just 2%, thus strengthening the evidence and usage of the *EIA reference scenario.*

The UK perspective
If we focus on the UK, using 2002 generating capacity (12 GWe) from the *NEA/IAEA Red Book,* and applying the MIT base assumptions, the UK would be calculated to require an annual mass of 2,013 tonnes of uranium. The *NEA/IAEA Red Book* reports the actual uranium demand figure for the UK being 1,930 tonnes for 2002, just 4% below our calculated value. This clearly suggests that MIT operating assumptions provide more or less the same general result for UK operations despite the fact that the MIT assumptions are based on LWRs and the UK is made up of largely gas-cooled reactors (AGRs). It may be the case that UK reactors nevertheless have similar uranium demand characteristics, but this has not been tested for this report.

2.8 Comparison of Uranium Demand Projections

This section is complex as it brings together a range of assumptions, some are common to more than one projection (e.g. utilisation rates), while others are particular to that scenario (e.g. capacity growth rates).

Global demand projections obscure regional trends. In order to reveal regional patterns this section separates the analysis into regional trends. At this scale it compares our base case *EIA reference scenario* described in the previous section with other possible projections.

Firstly, as a cross check and to ensure our existing method is reliable, we turn to an alternative and simpler methodology for estimating demand. This alternative approach determines uranium demand from a top down approach using reported generation data and reported uranium demand data from WNA sources. This data is available for 2004 (generation) and 2005 (estimates for capacity and uranium demand) by the WNA for each country (and aggregating to region) generating power from uranium. The first part of the process is to obtain a simple uranium fuel to power output ratio in tonnes per GWh as follows:

[Current U Demand in Tonnes** (WNA, 2005)**] ÷ [Current GWh Generation** (WNA, 2005)**]
=
[Current t/GWh]

Uranium demand can then be estimated from the capacity projections in the *EIA reference scenario* - after having applied average regional utilisation rates from the WNA to the projected GWe capacity throughout the forecast period as follows:

[Forecast GWe Capacity** (EIA reference, 2005)**] x [Current Hours of Utilisation** (WNA, 2005)**]
=
[Forecast GWh]

Finally:

[Current t/GWh] x [Forecast GWh] = [Forecast U Demand]

For simplicity, regional utilisation rates and average regional t/GWh uranium fuel use are held constant into the future to obtain a simple forecast for uranium demand.

Fixing these t/GWh and utilisation parameters is valid since nuclear capacity generally runs at base load (apart from regular maintenance outages), and so historically year-to-year variability has been relatively stable, but still flexible.

Similarly, nuclear technology worldwide has roughly the same level of fuel to power output efficiency and despite expected efficiency improvements in the future; for the purposes of illustrating different projections, this a reasonable approach.

Demand calculations are also provided in the *Red Book* to 2020, and so with this, we are able to determine a series of uranium demand projections using the three following methods, the results of which are illustrated in
Figure 11:

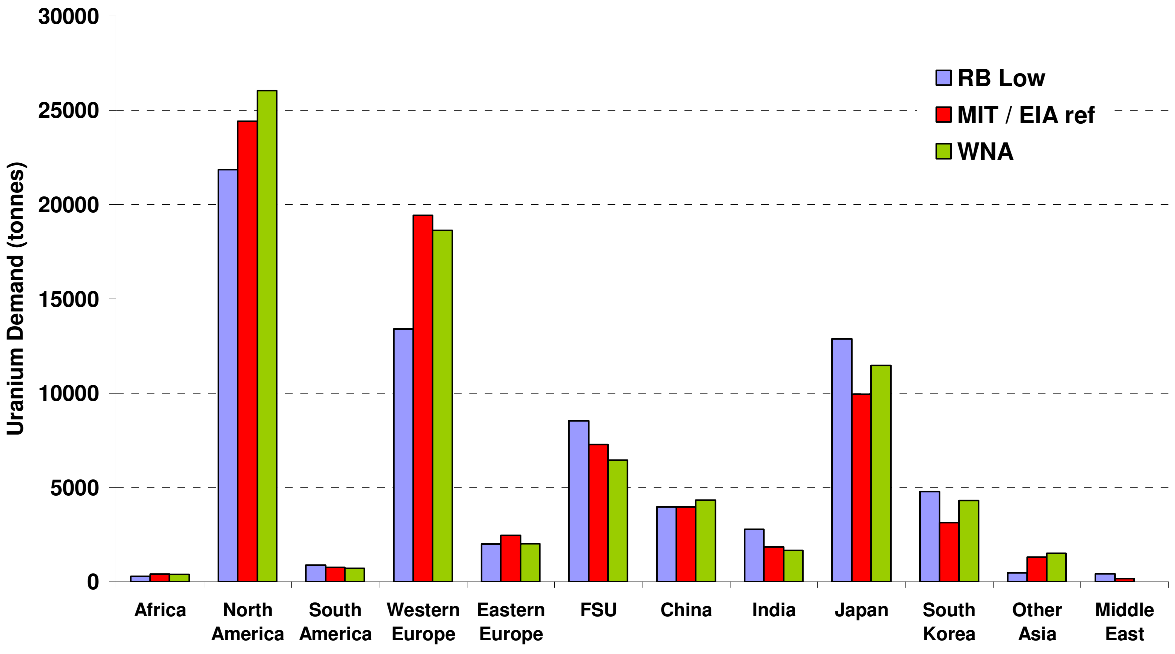
a) A WNA capacity projection (using simple WNA fuel conversion and WNA 2004 utilisation for each region)

b) An EIA reference projection for capacity (using MIT fuel conversions and WNA 2004 utilisation for each region)

c) The *Red Book Low projection* for uranium demand for each region.

Figure 11

Demand projection comparison for 2020



With some notable exceptions, there is close agreement between the uranium demand projections. Our base case *EIA reference projection* using MIT fuel conversion assumptions is very closely aligned with the *EIA reference projection* using the WNA uranium ratio assumption. Since both assume fixed utilisation rates (and technical specifications) this should not be surprising. Confidence in the validity of each approach may be improved by such a positive triangulation.

Western Europe and North America show the largest absolute differences between the *Red Book low scenario* and our base case *EIA/ MIT reference scenario*. In the most extreme case, Western Europe, the *Red Book low scenario* is 30% lower; 6% of this difference in projected uranium demand for Western Europe can be attributed to difference in capacity projections. If current utilisation in Western Europe of 82% were to increase to the US average level of 92%, a further 11% the difference in uranium demand could be accounted for.

Part of the remaining 13% gap lies in the different technical assumptions made in the MIT fuel conversion assumptions and the *Red Book* where not all of these are specified in the latter. However, the gap can also be explained by the expectation of advancements in reactor design that that may be assumed in the *Red Book* scenarios.

The next section gives details on – and tests the demand sensitivity of - the technical assumptions used in the MIT fuel conversion methodology (which in turn contributes to the EIA driven *base case* scenario upon which our final *base case* analysis on demand is made). Following this, additional comment is provided on the implications of technological advance up to 2025.

2.9 Assumptions and Sensitivities

The *EIA reference/MIT scenario* described above adopts the following assumptions, suggested by MIT. Each of these assumptions are adopted in our base case:

- Technology performance remains unchanged (i.e. there is no improvement in efficiency or burn-up)
- Thermal efficiency of 33% (thermal input / electrical output)
- Natural enrichment of 0.71% of uranium
- Burn-up of 50 GWd / MTIHM (Gigawatt days per metric tonne initial heavy metal)
- Required enrichment of 4.51% (given a burn-up of 50 GWd / MTIHM)
- Tails at 0.30% (U-235 content)
- Fuel management system uses three fuel batches. This means that the fraction of the core refuelled per cycle is 1/3
- MOX fuel does not make a significant contribution (see next section).

MIT fuel assumptions are focused on the technical characteristics of *Light Water Reactors* (LWR), and specifically *Pressurised Water Reactors* (PWR), typical of those employed widely across the world today. Other LWRs employed include *Boiling Water Reactors* (BWR), and account for a much smaller percentage of world nuclear capacity. The key differences are that PWRs require lower initial fuel enrichment and achieve a lower burn-up, which would slightly decrease the required natural uranium feed (i.e. uranium demand estimates for this parameter may be slightly conservative).

PWRs account for 237 GWe of existing capacity, and BWRs 81 GWe. Since global capacity is just over 360 GWe, these LWRs combined account for 88% of the world total[13]. Moreover, they also account for 88% of those 29.6 GWe of nuclear reactors currently under construction or recently completed, most of these are PWR types[14].

While the dominance of LWRs makes it reasonable to base the methodology upon it, it is important to recognise that the 12% that are not LWRs reduce the modelling precision to some extent.

Also, the MIT fuel burn characteristics appear to match the uranium demand in UK reactors, even though there is only on LWR in the country, Sizewell B. Both UK AGRs and LWRs worldwide use enriched UO_2 as a fuel, the key differences being between the reactors the moderators and coolant systems (light water versus CO_2 gas). However, the fuel burn characteristics are largely similar between these reactor types and so we would expect the fuel burn rates to differ only slightly.

Figure 12

Sensitivity of demand projections by technical assumption

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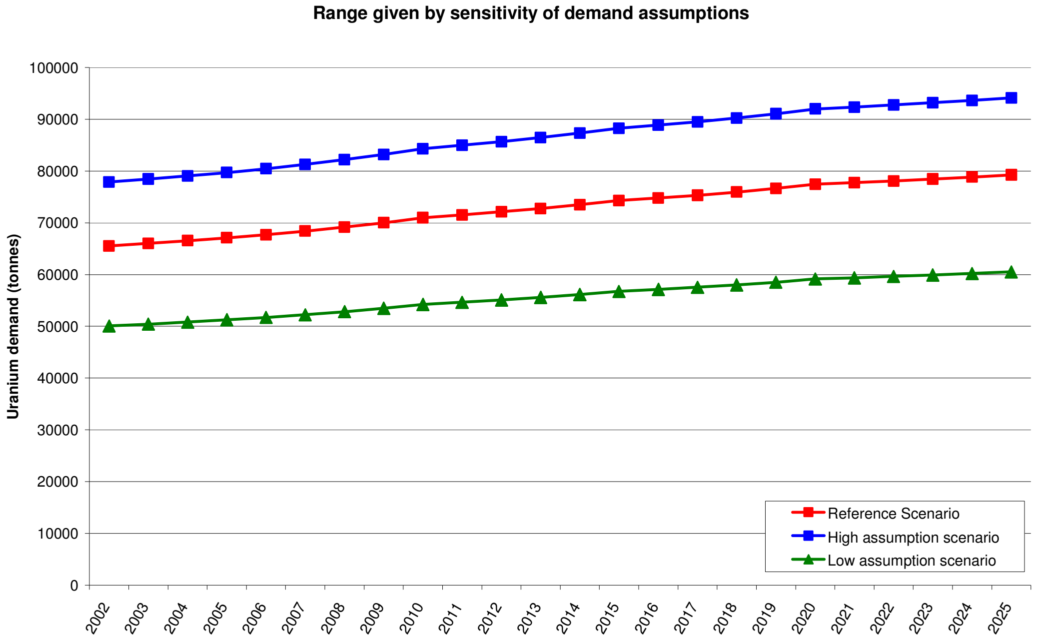
[13] Information and Issue Briefs – “Nuclear Power Reactors”, *WNA* (Oct 2005)
[14] Information and Issue Briefs – “Plans for New Reactors Worldwide”, *WNA* (Apr 2005)

Since the MIT methodology is available in relatively fine detail, it is possible to test these and utilisation sensitivities of each of the assumptions listed above.
Figure 12 shows the percentage change in demand implied by an alteration of each assumption (relative to the reference case). The reference case is as described above, with the exception of utilisation. This is fixed to 80% for the purposes of comparison. Each of the adjustments is technically feasible over the next few decades according to the MIT.

2.10 Summary of Sensitivities

- As expected the impact of altering utilisation factors from 80% to 70% or 90% is almost linear and produces a swing of +/- 12% from the reference.
- A high burn-up scenario of 100 GWd / MITHM is not currently possible (base assumption being 50 GWd / MTIHM), but actually has a limited impact on demand at just 5%. Counter-intuitively, high burn-up can *increase* demand because it has a knock-on effect on the required enrichment level, leading to greater uranium demand for the enrichment process – although this depends on the reactor design (see Chapter 1).
- Adopting a 5-batch fuel management scheme would reduce demand by 10%. 3-batches are typical in the US according to the MIT.
- Tails assays can alter demand significantly. This is determined by the price of uranium at the enrichment stage. Tails assays are currently falling, or being "stripped" i.e. the proportion of U-235 in enrichment waste is less, as increases in the relative uranium fuel price. Over the next few years the typical amount of U-235 in the tails assay may well be closer to 0.25% than 0.30% (our base assumption).
- The scenarios result from the combination of all the sensitivities and show the highest and lowest demand ranges around the base case. The scenarios are presented against the reference scenario in Figure 13 below. This is intended to indicate a plausible range.
- The extent of the range is +18% and -24%, which is equivalent to a swing of +9000 tonnes U per year down to -12,000 tonnes per year. The main drivers are: power station utilisation; tails assay (driven by uranium prices); and fuel batch management are most likely to create the biggest swings in uranium demand. They are driven by economics prevailing at any time in the market and less by technical advancement. These market driven parameters may reduce the impacts of improvements in technical factors such as burn-up performance and thermal efficiency.

Figure 13



2.11 Implications of Technological Advancements

The introduction of radically different reactor types naturally has the capability to affect uranium demand significantly in the future. However, several factors reduce the significance of technological advance (with regards to uranium demand) over the period to 2025:

a) The small proportion of additions compared to the existing fleet. For example. around 30 GWe of capacity is expected to be introduced in the period between 2005 and 2010, against a global total of around 360 GWe operating in 2005.

b) The dominance of LWR in the existing fleet – much of which are being considered for plant-life extension. Dungeness B was recently awarded a ten year life extension, which allows it to operate out to (at least) 2018[15].

c) The fact that 88% of those under construction are LWR – i.e. LWR remains the most popular choice of reactor type, it is likely to continue to make a significant contribution to additional operating capacity into the 2020s.

d) The Generation IV roadmap targets 2025 for the initial deployment of revolutionary technologies, yet difficulties introducing such designs can be expected.

Although there are a number of technologies undergoing research and development, the MIT argues that research funding should only be made available to advanced LWR reactors and to the development of High Temperature Gas Reactors (on the basis of cost, distance to deployment and non-proliferation concerns).

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[15] "10-year life extension at Dungeness B nuclear power station", *British Energy* (Sep 2005). http://www.british-energy.com/article.php?article=99

Generation III Reactors (now to 2030)

Reactor designs are usually described as *evolutionary* or *revolutionary*. The latest designs are described as Generation III, and are evolutionary – focusing on efficiency and cost savings in existing reactors (usually LWRs). These reactors are being seriously considered in countries across the world, including the UK.

One of the most promising reactor designs, the Westinghouse AP-1000, has received final design approval from the US *Nuclear Regulatory Commission* (NRC) and is expected to gain full design certification in 2005. Capital costs are commercially acceptable and construction periods are relatively short. It is under active consideration for building in China, Europe and the USA, and is capable of running on a full MOX core if required.

Another reactor design that is showing commercial attractiveness is that designed by Framatome ANP which has developed a large (1,600 MWe) European pressurised water reactor (EPR). This design was confirmed in mid-1995 as the new standard design for France and received French design approval in 2004. It is derived from the French N4 and German Konvoi reactors and is expected to provide power about 10% cheaper than the N4. It will operate flexibly to follow loads, have fuel burn-up of 65 GWd/t and the highest thermal efficiency of any light water reactor, at 36%. Utilisation is expected to be very high at 92% over a 60-year service life. The first unit is to commence construction in Finland, the second at Flamanville in France. The EPR is also undergoing review in the USA with intention of a design certification application in 2007.

Together with German utilities and safety authorities, Framatome ANP is also developing another evolutionary design, the SWR 1000, a 1000-1290 MWe BWR. The design was completed in 1999 and development continues, with US design certification being sought. As well as many passive safety features, the reactor is simpler overall and uses high-burn-up fuels, giving it refuelling intervals of up to 24 months and is ready for commercial deployment.

One option in the short to medium term, the CANDU reactor, is seen negatively by the MIT. The EIA also note that "the continuous process of refuelling- CANDU- PHWRs have raised proliferation concerns as has the high Pu-239 content of the spent fuel". The existing CANDU reactors reduce uranium fuel demand by approximately 25%, according to a paper by the IAEA[16]. However, CANDUs currently hold a small share of the world market, totalling just eight reactors (NEA/IAEA *Red Book*).

The ACR-700 (Advanced CANDU Reactor) is designed to "run on low-enriched uranium (about 1.5-2.0% U-235) with a high burn-up; this has the effect of extending the fuel life by about three times", according to the WNA. Were such designs to become popular, there would clearly be a significant implication for demand in the second quarter of the 21st Century.

Generation IV Reactors (post-2030)

Revolutionary reactor designs are known as *Generation IV*. These typically have significantly different operating characteristics than present technologies, and would thus have a large impact on demand. Six technologies were chosen as research priorities by the ten nations

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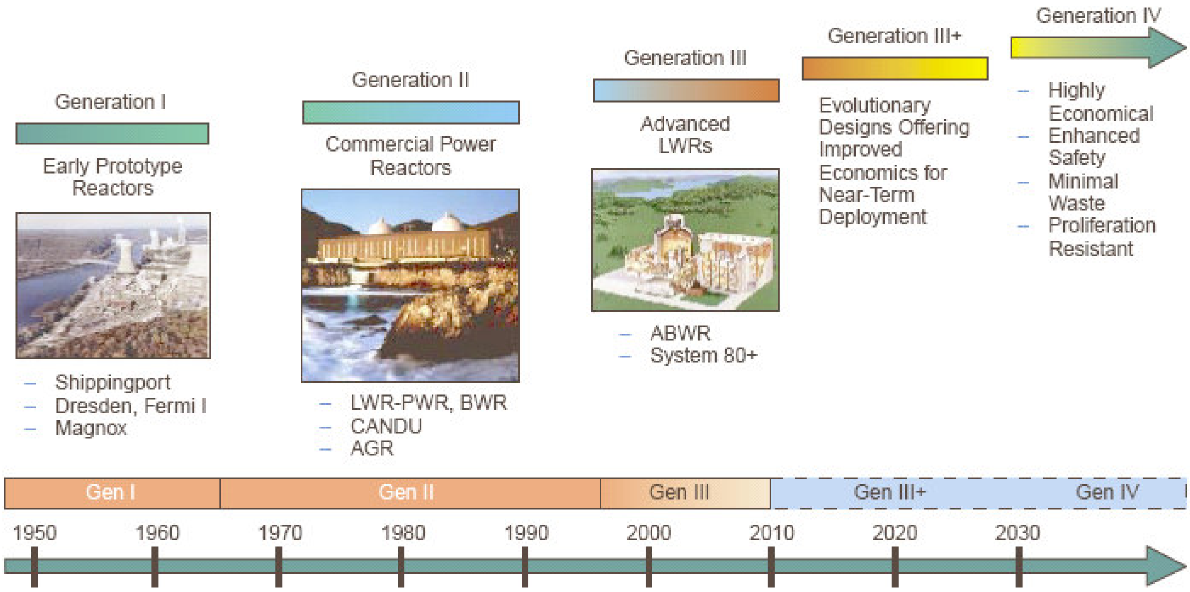
[16] "Innovative Technologies for Nuclear Power and the Nuclear Fuel Cycle", Conference and Symposium Papers 24P, *IAEA* (Jun 2003), www-pub.iaea.org/mtcd/publications/pdf/csps-24-p/csp-24_01_web.pdf

involved in the Generation IV roadmap project[17]. Half of which are based on fast reactor (fast breeder) technology, and the rest of which are based on conventional technology. The project has produced the following diagram. Note that Generation IV projects are typically not expected to be viable before 2030 (see Figure 14)

Figure 14



Source: Generation IV International Forum, OECD (2005)

The introduction of Fast Breeder Reactors would radically alter demand scenarios – reducing uranium demand by perhaps 60% according to MIT[18]. A fast breeder reactor is capable of producing more fissile isotopes than it consumes, making it possible to provide a growing energy resource that does not require a continuing supply of uranium 235 or plutonium 239 after an initial investment of fissile fuel at the beginning of its life.

Fast reactor technology is the generic term for technologies which include the fast breeder design. Such designs are very demanding and more capital intensive than LWR technology. A fast reactor power generation economy would also bring reprocessing and large amounts of fissile material with weapons potential into commercial use.

2.12 Mixed Oxide Fuel (MOX)

MOX is a means to "burn" the plutonium remaining in spent reactor fuel to provide energy and make electricity[19]. Currently, about 2% of new fuel is MOX, but this is increasing. MOX production capacity is presently around 300 tonnes per year, and is based in Belgium, France, the UK, Japan and Russia. According to the WNA:

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[17] "A Technology Roadmap for Generation IV Nuclear Energy Systems", Generation IV International Forum, *OECD* (2005), http://www.gen-4.org/Technology/roadmap.htm

[18] Appendix 4 – "Future of Nuclear Power", Beckjord E S et al,MIT (2003), http://web.mit.edu/nuclearpower/

[19] Nuclear Issues Briefing Paper 42 – "MOX Oxide Fuel", Uranium Information Centre (Jul 2003), http://www.uic.com.au/nip42.htm

> "*At present the output of reprocessing plants exceeds the rate of plutonium usage in MOX, resulting in inventories of plutonium in several countries. These stocks are expected to reach nearly 200 tonnes [of separated plutonium] before they start to decline after 2005 as MOX use increases. By 2010 production and use of plutonium in MOX are expected to be more in balance, with MOX supplying about 5% of world reactor fuel requirements*."

MOX has an impact on uranium demand since it is essentially substituted for uranium oxide fuel (UOX). Here an important distinction must be made: demand for reactor fuel does not decrease because of MOX, but rather fuel is recycled so that demand for primary uranium fuel is reduced.

Currently, the use of MOX does not significantly alter world uranium demand, because only a relatively small number of reactors are currently using it (NEA/IAEA *Red Book*). However, it is expected to make an increasing contribution over the next few years – and could reduce demand for uranium ore to some extent.

The WNA explains the purpose of MOX as follows:

> "*An advantage of MOX is that the fissile concentration of the fuel can be increased easily by adding a bit more plutonium, whereas enriching uranium to higher levels of U-235 is relatively expensive. As reactor operators seek to burn fuel harder and longer, increasing burn-up from around 30 GWd / MTIHM a few years ago to over 50 GWd / MTIHM now, MOX use becomes more attractive.*
>
> *With low uranium prices, reprocessing to separate plutonium for recycle as MOX is not itself economic, but coupled with reducing the volume of spent fuel to be managed, it can become so. Seven UO_2 fuel assemblies give rise to one MOX assembly plus some vitrified high-level waste, resulting in only about 35% of the volume, mass and cost of disposal.*"

Weapons- Grade Plutonium

Another key driver for MOX has been the decommissioning of nuclear weapons. In June 2000, the USA and Russia agreed to dispose of 34 tonnes each of weapons-grade plutonium by 2014[20]. As the WNA suggests: "Input weapons-grade plutonium might need to be mixed with reactor grade material, but using such MOX as 30% of the fuel in one third of the world's reactor capacity would remove about 15 tonnes of warhead plutonium per year. This would amount to burning 3000 warheads per year to produce 110 billion kWh of electricity."[21]

However, the MIT cautioned the US government against pursuing MOX. Fundamental to their argument is that non-proliferation activity should focus on minimising the proliferation risks of nuclear fuel cycle operation (as opposed to focusing primarily on decommissioning).

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[20] "Backgrounder on Mixed Oxide Fuel", *NRC* (May 2005), http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/mox-bg.pdf

[21] Nuclear Issues Briefing Paper 4 – "Military Warheads as a Source of Nuclear Fuel", *UIC* (Nov 2004), http://www.uic.com.au/nip04.htm

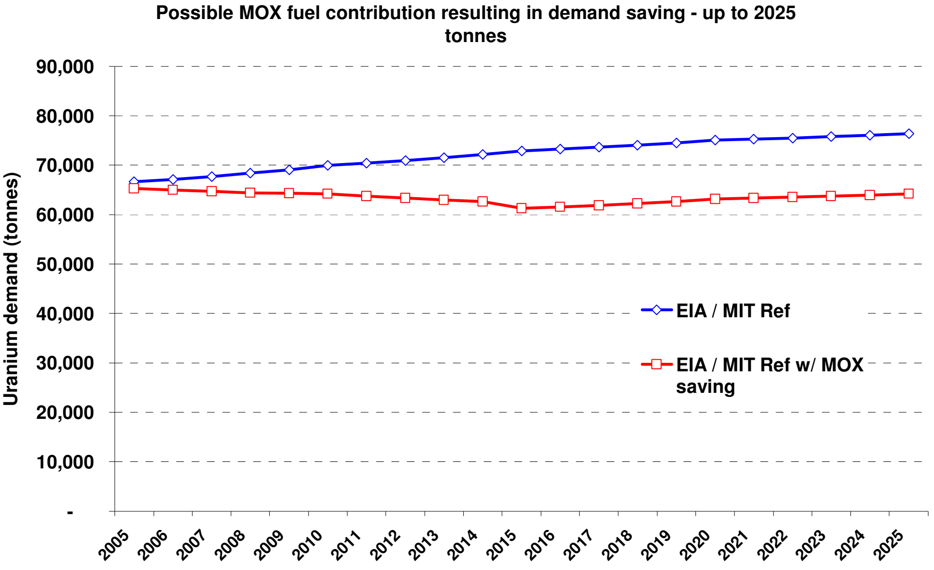
At present, the US is accelerating plans to convert 34 tonnes of Russian surplus weapons-grade plutonium into MOX, as well as an equal amount of US plutonium itself.[22] However, the US Department of Energy has stated that it has no capability and no plans to reprocess either used reactor or MOX fuel.[23]

Plutonium from Civil Reactor Waste

Once existing supplies of plutonium have been consumed, the contribution of MOX is limited by the stream of waste from traditional reactor use (usually described as "UOX", since Uranium Oxide is the only fuel in this case).

The impact on uranium demand can be seen in Figure 15. Data have been calculated using the MIT methodology given in detail in the *Future of Nuclear Power* report. The demand saving due to MOX is limited, since it is dependent on the number of operating uranium oxide reactors - MOX fuel is produced from UOX reactor "waste".

Figure 15



More waste would be required to feed more MOX reprocessing, and beyond 16% there is no extra waste fuel to reprocess. In the short term there is a supply of historical nuclear waste available for reprocessing, as well as contribution from HEU (see Chapter 2 - Demand).

Savings have been phased in gradually until they reach the maximum in 2015, and so relatively low in early years.

MIT assume that burn-up of MOX is the same as for LWR: this is reasonable since "Currently, MOX fuel in LWR is generally irradiated to a burn-up lower than 50 GWd-/-MTIHM, but parity with UOX is anticipated as experience is gained.[24]

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[22] Statement of Linton Brook, Acting Under Secretary of Energy and Administrator for National Security, *U.S. DOE* (Mar 2003) http://www.house.gov/hasc/openingstatementsandpressreleases/108thcongress/03-03-04brooks.html

[23] Frequently Asked Questions About Mixed Oxide Fuel, *US Nuclear Regulatory Commission* (Jun 2005), http://www.nrc.gov/materials/fuel-cycle-fac/mox/faq.html#3

[24] Appendix 4 – "Future of Nuclear Power", Beckjord E S et al,*MIT* (2003), http://web.mit.edu/nuclearpower/

In this full MOX saving scenario, annual reduction in uranium demand is approximately 16% by 2015, however, a more likely forecast uses current estimates where MOX is expected to provide 5% of reactor fuel by 2010 (*Red Book*). According to MIT, the equivalent of only 9 GWe of capacity is currently provided by MOX fuel (2.5% of global capacity). The MOX saving in Figure 15 is thus best seen as a maximum rather than a realistic projection.

3 Supply

3.1 Introduction to Supply

This chapter covers the supply side aspects of uranium markets, focusing on the period up until 2025. It explores the current uranium reserves and production data, and focuses on the geographic distribution of each.

Uranium is a relatively common element, occurring in most rocks in concentrations of 2 to 4 parts per million. It is as common in the earth's crust as tin, tungsten and molybdenum.[25] Uranium is also present in low concentrations in seawater. However, current prices for extraction are reportedly five to ten times the cost of a typical uranium mine at present.[26] Concentrated uranium ores are found in just a few places, usually in hard rock or sandstone.[27] The largest deposits of uranium ore are found in Australia, Kazakhstan and Canada. Much of the high-grade deposits are found in Canada. In particular, the Saskatchewan mine has ore grades 100 times the global average (Cameco).

Uranium resources are not limited to primary production. Stockpiling in the civilian nuclear industry over recent decades; "diluted" weapons-grade uranium; and re-enrichment activities, each make significant contributions to current uranium fuel supplies. In addition, mixed oxide fuel (MOX) has the potential to make an important supply contribution in the medium term.

These secondary supplies will become less significant over the coming decades, with the possible exception of MOX. Supply side security considerations therefore differ according to the duration of time selected for analysis. In this report we distinguish between the long term reserve data (how much is there in the ground?), and the short to medium term availability (what is the extent of primary and secondary supply capabilities over the next 10-15 years?). The implications for the security of uranium supply will be considered in Chapter 4 - Analysis of Resource Availability, when supply analysis is combined with demand projections.

3.2 Uranium Reserves (the Long Term)

In a manner similar to oil and gas, uranium reserves are defined according to the probability of their existence and the cost (or technical feasibility) of their extraction. Although several categorisation systems exist, the most recognised is contained in the *Red Book*. Categories

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[25] "What is Uranium? How does it work?" *Uranium Information Centre UIC* (2005) http://www.uic.com.au/uran.htm

[26] Annex 8 – "Evaluation of Cost of Seawater Uranium Recovery and Technical Problems toward Implementation", *Analytical Centre for Non-proliferation* (2005), http://npc.sarov.ru/english/digest/132004/appendix8.html

[27] "Uranium", *Cameco* (Apr 2005), http://www.cameco.com/uranium_101/uranium_science/uranium/

given in this report are therefore aligned to this system. Very low-grade resources or those from which uranium is only recoverable as a minor by-product are considered *unconventional resources*. These resources, including uranium from seawater, are not likely to play a role in the next 25 years and are accordingly given less emphasis in this report.

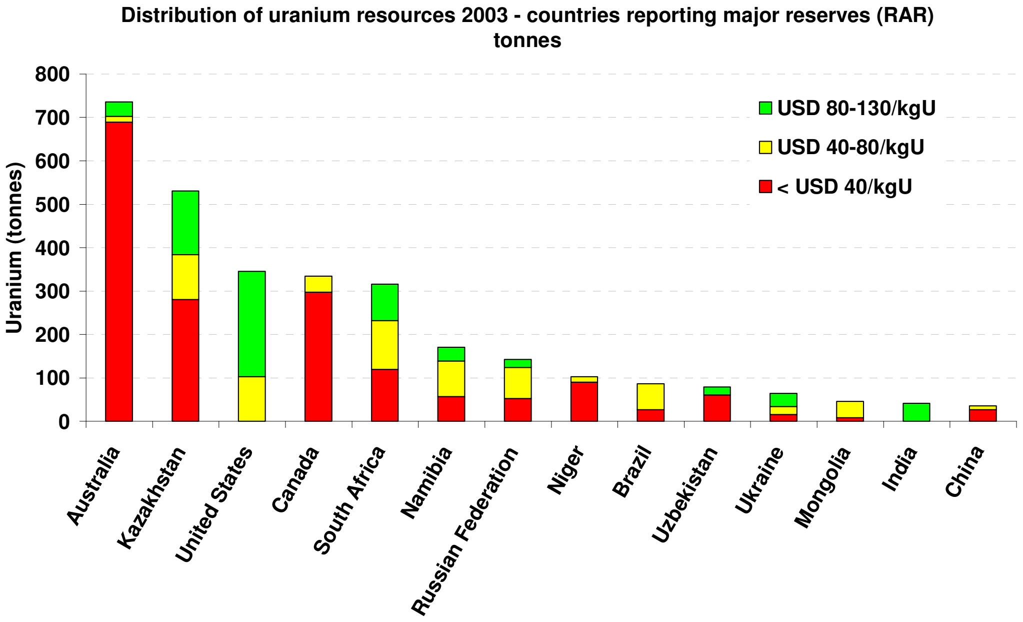
Conventional resources are those that have an established history of production; where uranium is either a primary product, co-product or an important by-product, for example, from the mining of copper and gold (*Red Book*). Conventional resources are further divided into four categories, according to different confidence levels in their occurrence. The details of this classification system, as defined in the NEA/IAEA *Red Book*, are given in Table 1 *NEA/IAEA Classification System*.

Reasonably Assured Resources (RAR) are known resources with detailed estimates, and are considered to have a high assurance of existence. The definition is broadly similar to the oil and gas category "proven reserves".

Estimated Additional Resources (I) or EAR (I) have been based on direct geological evidence, in extensions of well-explored deposits, or in deposits in which geological continuity has been established. However, the lack of detailed specific data prevents these resources from being classified RAR. Together, RAR and EAR (I) are classified as *Known Conventional Resources*. In all these categories the *Red Book* provides different levels of reserves at progressively costs of extraction: $40 / kg, $80 / kg and $130 / kg. This implies that certain reserves shall only become economic in the event of significant price increases (recent prices have exceeded $70 / kg). The latest *Red Book* (2004) contains the following figures for RAR (Figure 16). It is important to note that levels of accuracy may differ according to the country in which they are reported.

Estimated Additional Resources (II) and Speculative resources are considered *unknown conventional resources*, since there is less confidence in their occurrence.

Figure 16



While many countries hold uranium reserves, over 70% of global RAR are found in Australia, Kazakhstan, USA, Canada and South Africa. Australia has more than twice the volume of

RAR classified at < $40 / kg as its nearest rival, Kazakhstan. Four of these countries are members of the OECD. Kazakhstan and South Africa both currently have positive relationships with OECD countries.

Table 1 *NEA/IAEA Classification System*

Reasonably Assured Resources (RAR) refers to uranium that occurs in known mineral deposits of delineated size, grade and configuration such that the quantities which could be recovered within the given production cost ranges with currently proven mining and processing technology, can be specified. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of deposit characteristics. Reasonably Assured Resources have a high assurance of existence. Unless otherwise noted RAR are expressed in terms of quantities of uranium recoverable from mineable ore (see Recoverable Resources below).

Estimated Additional Resources – Category I (EAR-I) refers to uranium, in addition to RAR, that is inferred to occur based on direct geological evidence, in extensions of well-explored deposits, or in deposits in which geological continuity has been established but where specific data, including measurements of the deposits, and knowledge of the deposit's characteristics are considered to be inadequate to classify the resource as RAR. Estimates of tonnage, grade and cost of further delineation and recovery are based on such sampling as is available and on knowledge of the deposit characteristics as determined in the best known parts of the deposit or in similar deposits. Less reliance can be placed on the estimates in this category than on those for RAR. Unless otherwise noted, EAR-I are expressed in terms of quantities of uranium recoverable from mineable ore (see Recoverable Resources below).

Estimated Additional Resources – Category II (EAR-II) refers to uranium, in addition to EAR-I, that is expected to occur in deposits for which the evidence is mainly indirect and which are believed to exist in well-defined geological trends or areas of mineralisation with known deposits. Estimates of tonnage, grade and cost of discovery, delineation and recovery are based primarily on knowledge of deposit characteristics in known deposits within the respective trends or areas and on such sampling, geological, geophysical or geochemical evidence as may be available. Less reliance can be placed on the estimates in this category than on those for EAR-I. EAR-II are normally expressed in terms of uranium contained in mineable ore, i.e., *in situ* quantities.

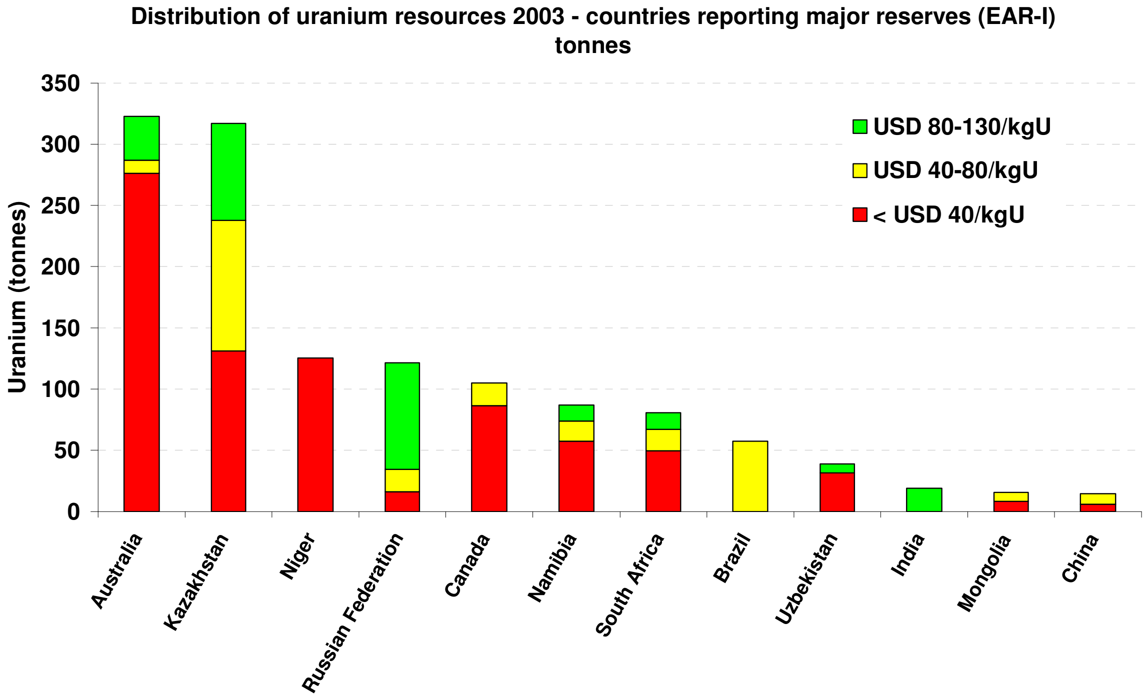
Speculative Resources (SR) refers to uranium, in addition to EAR-II, that is thought to exist, mostly on the basis of indirect evidence and geological extrapolations, in deposits discoverable with existing exploration techniques. The location of deposits envisaged in this category could generally be specified only as being somewhere within a given region or geological trend. As the term implies, the existence and size of such resources are speculative. SR are normally expressed in terms of uranium contained in mineable ore, i.e., *in situ* quantities.

Cost categories

The cost categories, in USs dollars ($) defined in the *Red Book* and used in this report are as follows: <$ 40 / kgU, <$ 80 / kgU, and < $130 / kg. All resource categories are defined in terms of costs of uranium recovered at the ore processing plant.

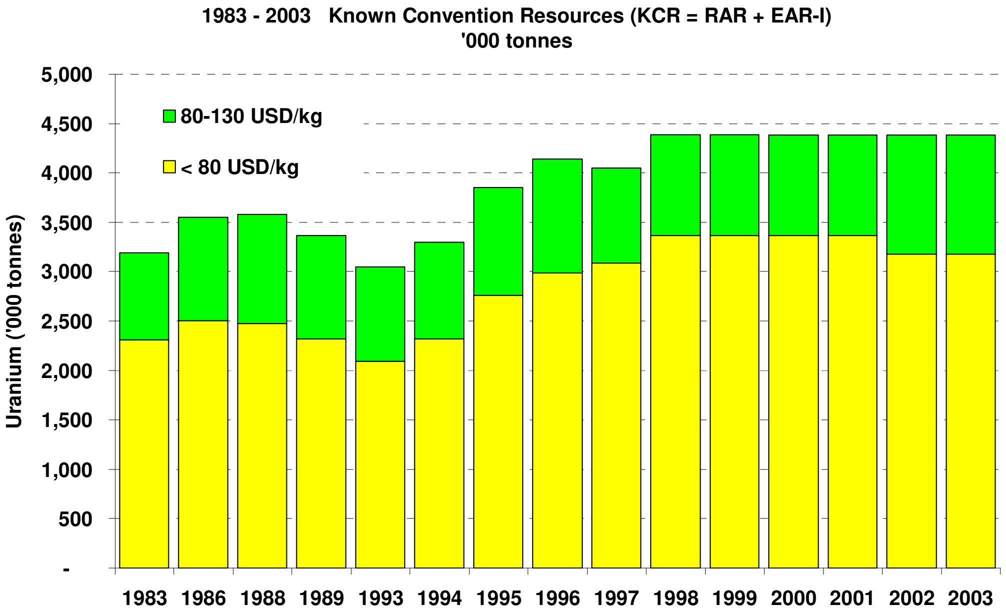
The picture is similar for *Estimated Additional Resources* (I):

Figure 17



However, the prominence of Kazakhstan has increased relative to Canada, the US and South Africa; this suggests that it may be increasingly important in the future (i.e. when RAR begin to run out). *Known Conventional Resources* are those that have been investigated and verified with some confidence. As a consequence, reserve figures are liable to be adjusted whenever exploration activities provide new or stronger evidence. Figure 18 illustrates the significance of this issue. It shows the resource figures provided in the *Red Book* over the last 20 years.

Figure 18

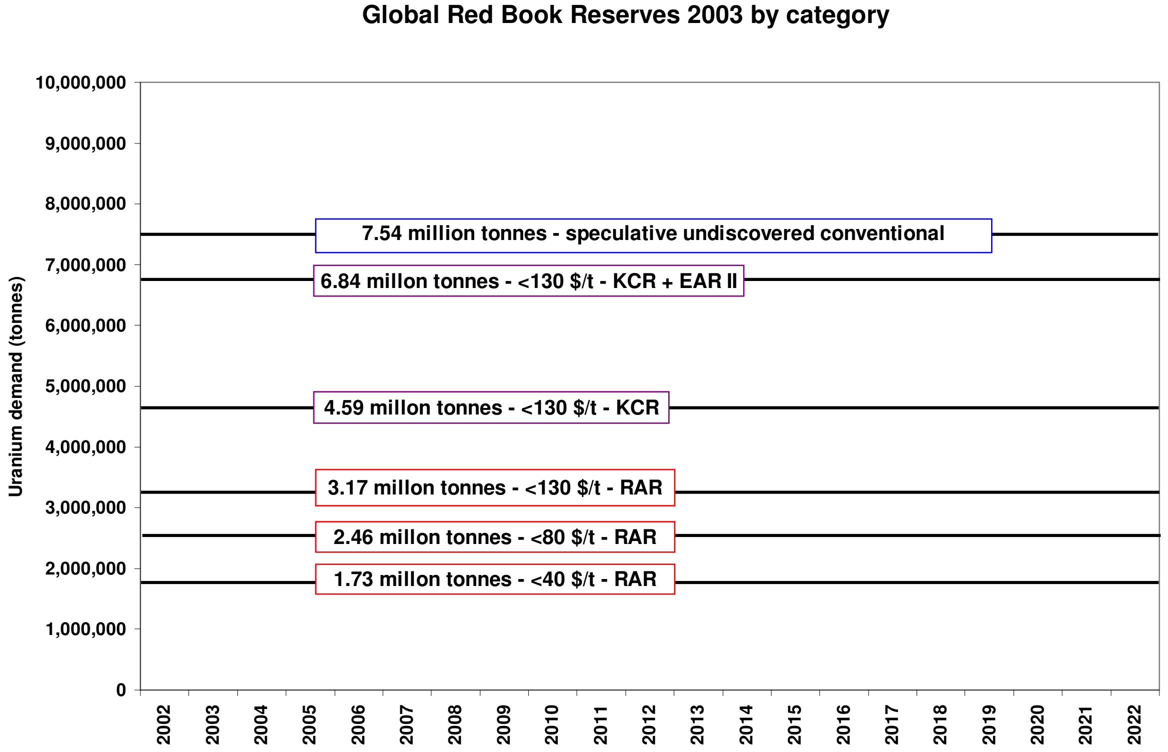


Known resources have therefore *increased* over the period, despite extraction. In fact, known resources <$80 / kg have increased by over 40%. As a result, any analysis of the lifetime of resources based on KCR must be treated with caution.

According to the *Red Book*, exploration activities remain concentrated primarily in areas in close proximity to known resources. Limited expenditures are directed toward "grass roots" exploration. It is therefore reasonable to deduce that the current leading reserve holders are the most likely to add new reserves over the short term. However, higher prices are beginning to stimulate more aggressive exploration.

By definition, reserve figures for unknown conventional resources can be considered even less reliable. However, they provide a useful if limited indication of the medium to long term supply availability:

Figure 19



Around 4.6 million tonnes of KCR are available below $130 / kg, with a further 2.2 million tonnes available as EAR II. The uppermost box in blue in Figure 19 describes speculative undiscovered conventional resources at 7.5 million tonnes, these outnumber all of the higher-confidence categories combined.

Discussion in the literature is often polarised, with one side arguing that high uranium markets will continue to lead to exploration and additional reserves, and the other that uranium is a non-renewable resources that will run out at some point.

The pessimistic camp suggests that resources are likely to run out before the end of the 21st century. It is represented in large part by the many campaigning groups hostile to nuclear. For example, the *International Physicians for the Prevention of Nuclear War* produced posters stating *Uranium will only last a few decades – what then?*[28] Technology and engineering lobbies that have interests in fast breeder reactors also highlight resource constraints (arguing that fast breeders would largely remove pressure on resources).

The positive camp – represented for instance by nuclear generating companies; other nuclear specialists; and by free marketeers – instead argue that any scarcity in resources will lead to exploration and/or technological advance – perhaps to fast breeder reactors or to the economic viability of extracting uranium from seawater. A good example is a recent position statement by the WNA:

> "*There is every reason to expect that the world supply of uranium, as of other metals, is sustainable, with adequate known resources being continuously replenished at least as fast as they are being used and 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."*[29]

Both arguments clearly have some merit – high prices will stimulate extraction and investment, but there remains a limited availability of the resource without significant technological advance. In any event, the nature of reserve uncertainty makes it impossible to give definite answers about when uranium resources will run out (or more accurately, become prohibitively expensive to extract). More detailed comparisons of supply and demand are provided in Chapter 4 - Analysis of Resource Availability.

3.3 Uranium Supply (the Short to Medium Term)

The section above focuses on the long term availability of uranium resources. As noted in the introduction, there is also a question about the availability of uranium in the immediate term and looking forward over the next 20 years. To assess this issue, current and planned production is significant, rather than long term resources.

Primary production of uranium is currently focused in eight countries, with contributions from several small producers such as Brazil and Germany. Figure 20 shows that Canada, Australia, Niger, Russia, Kazakhstan, Namibia, Uzbekistan and the US all make important contributions. Canada and Australia are clearly the dominant producers in the market.

Namibia and Niger together contributed around 15% of the global total in 2002. Kazakhstan and Uzbekistan contributed around 13% between them, and Russia around 8%. However, Kazakhstan is increasing its production at a rapid rate (see Chapter 4 - Analysis of Resource Availability for more details).

The short term supply issue is complicated by *secondary* sources of fuel. These supplies are partly the result of stockpiling during the 1970s – as a response to perceived insecurity in oil supplies – and partly the result of military activity. The latter contributes through diluted

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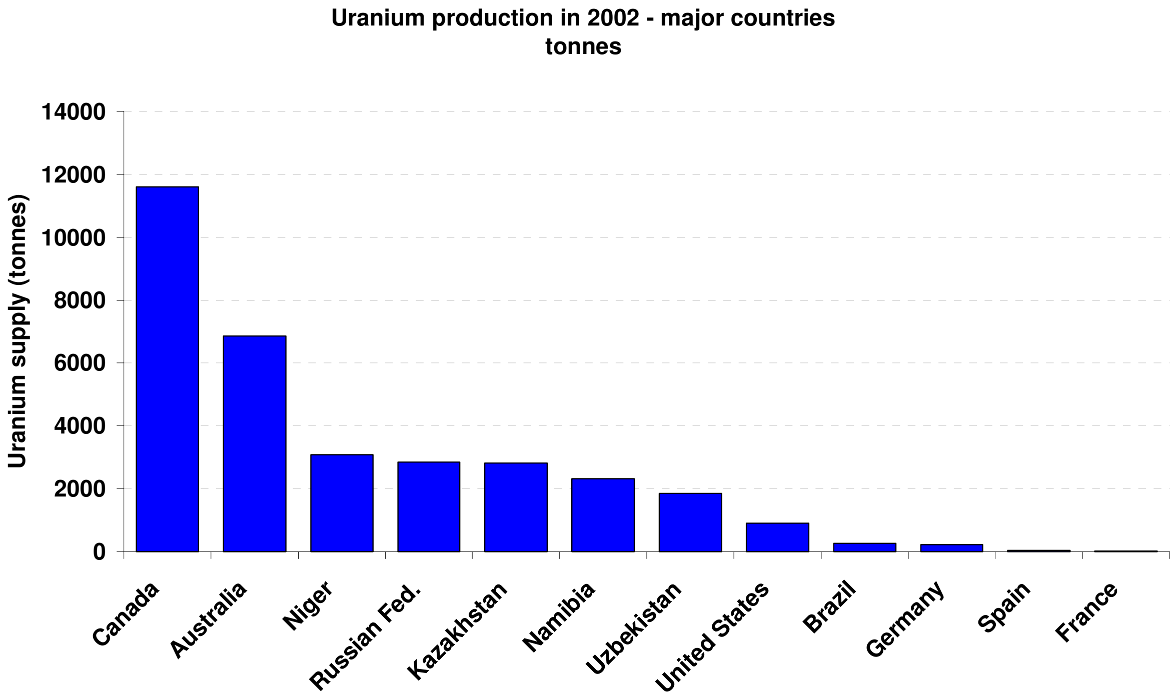
[28] "Nuclear Power is a Dead End", *International Physicians for the Prevention of Nuclear War*, http://www.facts-on-nuclear-energy.info/download/en_1a1.pdf

[29] "Can Uranium Supplies Sustain the Global Nuclear Renaissance", *WNA* (Jul 2005), http://www.uic.com.au/WNA-UraniumSustainability.pdf

Highly Enriched Uranium (HEU), which can be "blended down" into the *Low Enriched Uranium* (LEU) used in power plants.

Figure 20



Although secondary sources are now declining, they continue to account for around 60% of all supply in 2005. Beyond 2020, however, they are likely to be relatively insignificant.[30]

Table 2 *Secondary supplies of Uranium* gives detail on the main categories of secondary supplies (details are from the *Red Book* and the WNA website).

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[30] "Analysis of Uranium Supply to 2050", *IAEA* (May 2001), http://www.pub.iaea.org/MTCD/publications/PDF/Pub1104_scr.pdf

Table 2 Secondary supplies of Uranium

Civilian inventories

These include strategic stocks, pipeline inventory and excess stocks available to the market. Utilities are believed to hold the majority of commercial stocks because many utilities have policies that require carrying the equivalent of one to two years of natural uranium requirements. Despite the importance of this secondary source of uranium, relatively little is known about the size of available stocks because few countries are able to provide detailed information on stockpiles held by producers, consumers or governments mainly due to confidentiality concerns.

Military inventories

In February 1993, Russia agreed to blend down 500 metric tons of Highly Enriched Uranium (HEU) to low-enriched uranium for peaceful use in commercial reactors over 20 years (The *Megatons to Megawatts* programme). The annual deliveries of 30 tonnes HEU would displace about 9,000 tonnes of natural uranium. This represents about 10-13% of world annual uranium requirements through to 2013.

The US has committed to the disposition of about 174 tonnes of surplus HEU with about 153 tonnes planned to be eventually blended down for use as LEU fuel in research and commercial reactors. About 39 tonnes of this HEU has already been converted. The remainder will be converted over the next several years. There is some uncertainty over the future of the HEU agreement after 2013.

MOX

The demand implications of MOX fuel were considered in Chapter 2 - Demand. However, MOX is also clearly a supply issue. As of January 2001, the 2003 NEA *Brown Book* reports that 250,000 tonnes of heavy metal (spent fuel) have been discharged from power reactors. About 170,000 tonnes remain in storage as spent nuclear fuel with the remainder having been or intended to be reprocessed. The *Brown Book* considers that to date MOX has not made a significant impact on demand, but is likely to contribute 5% of supply by 2010.

Tails

Tails are the waste product from the enrichment process (see Chapters 1 and 2). Russian firms have found it economic to use some of their enrichment capacity to re-enrich tails material from past enrichment operations. Russian enrichment capacity was previously used to produce Highly Enriched Uranium for weapons purposes.

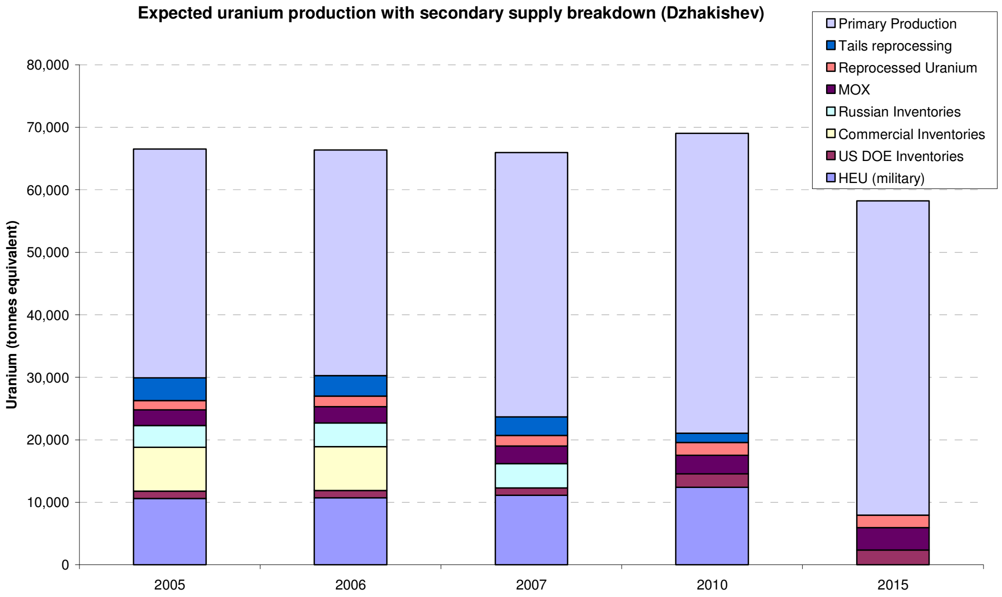
The exact extent to which re-enrichment has occurred in recent years in not known with any precision, but in the Uranium Institute estimated in 1998 that as much as 7000 tU equivalent per year might have been produced. This figure is, however, highly uncertain.

Some enrichment companies in Western countries have also sent quantities of their own tails material to Russia for re-enrichment, principally Urenco and Cogema. The resultant uranium has been estimated by the Euratom Supply Agency (ESA) to be equivalent to between 2000 and 2500 tonnes of natural uranium per year at present, of which 1000 to 2000 tonnes is expected to be used within the European Union (EU), with the remainder being exported.

Sources: *Red Book*; *Brown Book*; WNA website; Euratom ESA website

Data for the various secondary supply sources are scarce. Tables are provided in the Red Book for some of sources, but there are as many gaps as there are entries. Significant commercial and national interests exist that are a barrier to accurate reporting. In 2004 an analysis of the extent of secondary supplies was produced by Moukhtar Dzhakishev, President of the Kazach National Atomic Company *Kazatomprom*.[31] In the absence of detailed independent reporting, this is a valuable indication of the breakdown of secondary supplies:

Figure 21



The steep decline in 2015 is the result of uncertainty over future US-Russia agreements regarding the blending down of military HEU for civilian reactors - the first phase of the programme ends in 2013 and estimates were not included by Dzhakishev for 2015. This is not unreasonable since a number of experts have questioned whether an "HEU II" agreement will ever happen.[32]

As mentioned, there is a scarcity of information on secondary supplies. However, it is possible to compare the primary supply series in Figure 21 with *primary production capacity of existing, committed, planned and prospective centres* as defined by the *Red Book*. Figure 22 shows the distribution of this possibly supply – based on known conventional resources at <$80 / t.

The totals are higher than the primary production in Figure 21. For example, in 2010 Dzhakishev has used a figure of around 48,000 tonnes. For the same year in Figure 22 the figure is around 63,000. This can be explained by the fact that the totals in Figure 22 are for resources extractable at less than $80 per kg. Since prices are currently around $70 per kilo (>$30 per lb), one would not expect all of this capacity to be operational. Dzhakishev

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[31] "Uranium production in Kazakhstan as a potential source for covering the world uranium shortage", Dzhakishev (2004). Kazatomprom clearly have an interest in calling for additional investment in uranium resources. However, Dzhakishev is careful to explain that his supply data is more optimistic than NEA/IAEA.

[32] "Back from the Brink", *Connor* (2004)

explains that his primary supply estimates are actually more optimistic than NEA/IAEA. An important point is that while primary supply is expected to increase, and secondary supplies are expected to cancel out much of this gain in supply.

Figure 22

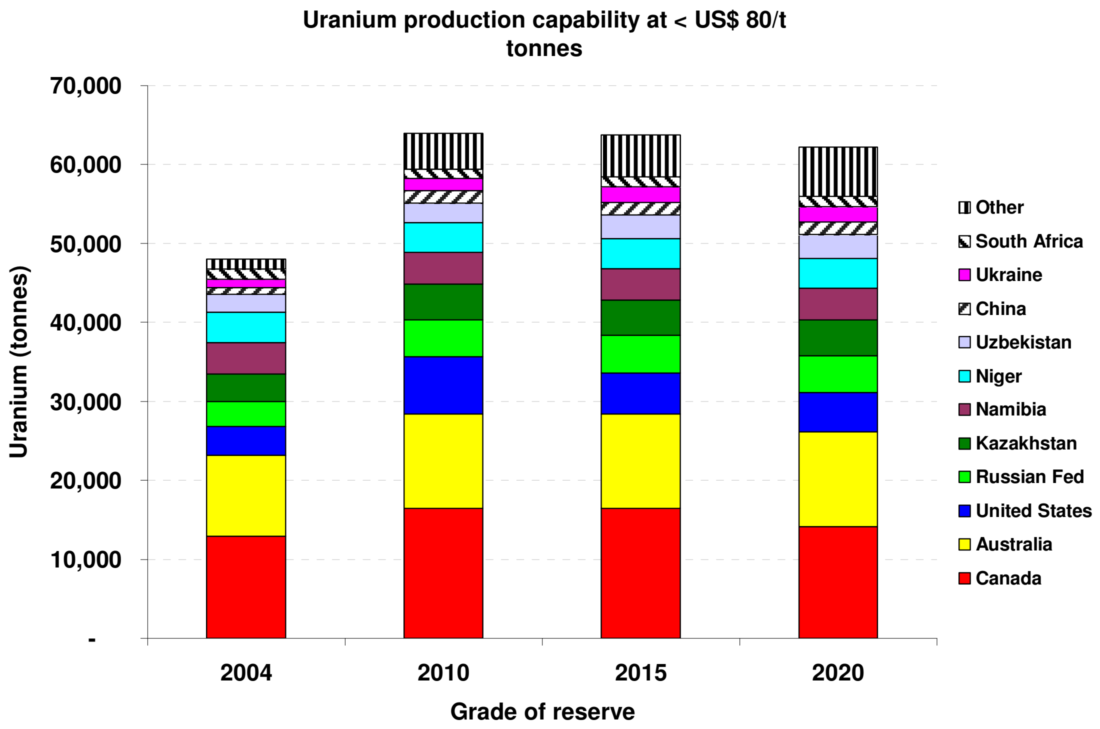

Table 3

	2004	2010	2015	2020
Canada	12,885	16,425	16,425	14,125
Australia	10,300	12,000	12,000	12,000
United States	3,600	7,200	5,200	5,000
Russian Fed	3,200	4,700	4,700	4,700
Kazakhstan	3,500	4,500	4,500	4,500
Namibia	4,000	4,000	4,000	4,000
Niger	3,800	3,800	3,800	3,800
Uzbekistan	2,300	2,500	3,000	3,000
China	850	1,560	1,560	1,560
Ukraine	1,000	1,500	2,000	2,000
South Africa	1,270	1,270	1,270	1,270
Brazil	340	1,100	1,100	1,100
Mongolia	-	1,100	1,100	1,100
India	230	880	1,560	2,890
Argentina	120	500	500	
Iran	-	410	410	410
Romania	100	300	300	400
Pakistan	65	110	200	250
Czech Republic	440	84	87	80
Total	**48,000**	**63,939**	**63,712**	**62,185**

Production capability, as expected given production data in Figure 22 and Table 3, is dominated by Canada and Australia; together these account for nearly half the total capability in 2004. A notable trend is that as we move towards 2020, capability begins to diversify – other countries increase relative to the large producers. On one level supply security is improved through increasing the number of potential sources. However, this benefit is possibly outweighed by the fact that EU trade relationships with Canada and Australia are relatively positive and stable.

3.4 Risks to Uranium Supply

As with oil and gas, the supply of uranium can be affected by a range of factors and actors. Investment in mines, conversion and enrichment are all important. They may by financed privately or by a national atomic company such as Kazakhatomprom. Government policy influences operation and investment through trade, planning, environmental, labour, and other policies. These issues are assessed in more depth in Chapter 4 - Analysis of Resource Availability.

Interruptions to supplies at the mining end of the industry (the upstream) can be caused by natural disaster; changes in regulations; loss of financial viability; unexpectedly small reserves at a site; technical or operational failures at a mine; or by political and social unrest. Interruptions are equally possible at conversion or enrichment facilities, or through obstructions to transport networks. It is important to note that uranium mines cannot easily respond to short term stress. It takes many years to find new mines, and developing existing mines can be problematic.

A recent Euratom Supply Agency report identified the following *top 10 risks* or concerns with regards Western uranium security of supply[33]:

1. Lack of investment in conversion
2. Lack of investment in new mines
3. Financial/legal difficulties for producers
4. Overregulation, frequent changes and lack of harmonisation in transport approvals/authorisations
5. Permanent closure of a uranium mine
6. Lack of ports open to nuclear transport - concentration of nuclear transport companies
7. Permanent closure of a conversion facility
8. Interruption of the US - Russia HEU Agreement
9. Uncertainty of US enrichment capacity in future
10. Delays of new projects due to licensing / environmental regulations.

It is notable that investment and regulation are a key concern – although interruptions at mines and ports are also included. The list is perhaps more representative of industry technical, legal and regulatory aspects than it is of broader geopolitical concerns. More specific strategic concerns are discussed in Chapter 4 - Analysis of Resource Availability.

One issue - both related to investment and extending beyond it – is the impact on and the rights of indigenous peoples in uranium mining areas. According to one estimate, 70% of the worlds uranium resources are located in the lands inhabited by indigenous peoples in Africa,

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[33] “Analysis of the Nuclear Fuel Availability at EU Level from a Security of Supply Perspective”, *Euratom Supply Agency* (Jun 2005), http://europa.eu.int/comm/euratom/docs/task_force_2005.pdf

Asia, Australia, and North and South America. Issues typically relate to environmental pollution, land rights and right to proceeds.

At the Jabiluka mine in Australia, tension and negotiation have existed between the Mirrar aborigines, ERA (a subsidiary of Rio Tinto) and the government for many years. In 2005 the Jabiluka Long Term Care and Maintenance Agreement was finally signed. This obliges ERA (and its successors) to secure Mirarr consent prior to any future mining development of uranium deposits at Jabiluka.

The European Parliament adopted a motion calling upon Australia to take action in this area in 1998. The motion notes that the Vienna Declaration adopted by the World Conference on Human Rights stresses the protection of Indigenous peoples' economic, social and cultural well-being including their distinct identities and cultures. A green group within the Swedish Parliament has also led a campaign on the issue. Clearly other international agreements such as the Convention on Biodiversity, and the Rio Declaration on Environment and Development are relevant here. It is also an issue UNESCO have been heavily involved in, including at Jabiluka.

These are complex issues that can clearly, amongst other issues, have a significant impact on resource availability. In practical terms, it can lead to long delays before otherwise economic mines are introduced.

4 Analysis of Resource Availability

4.1 Introduction

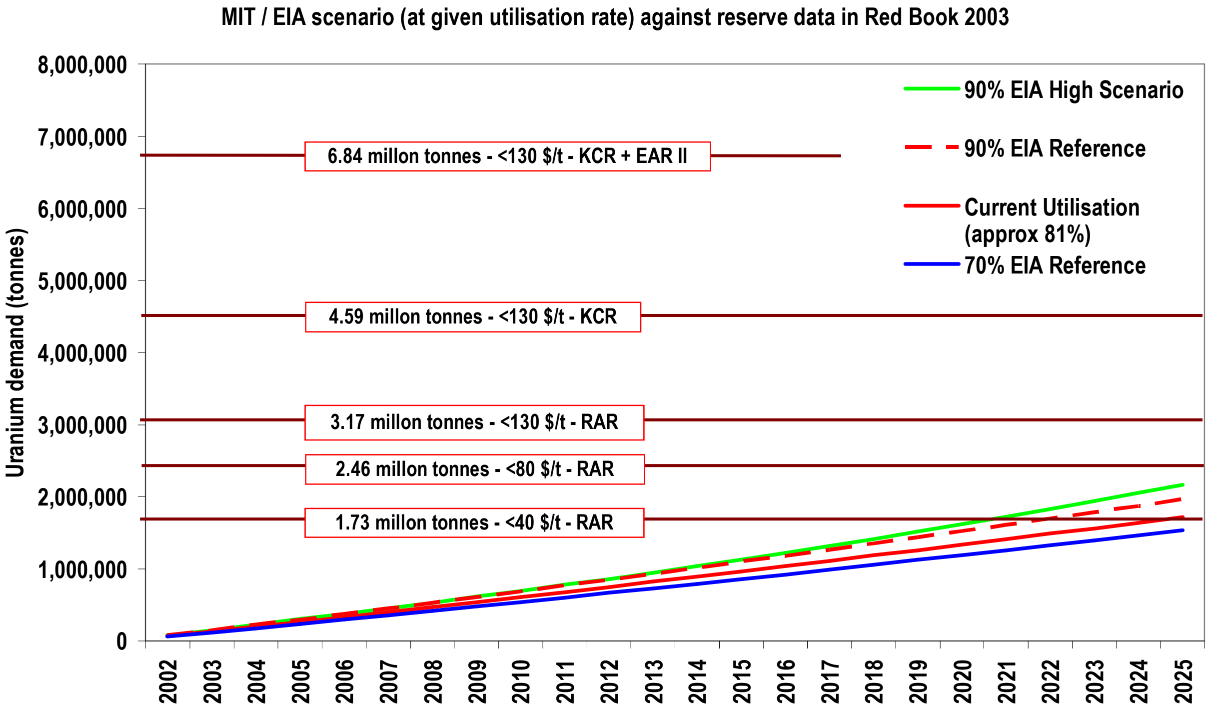
Having considered demand and supply separately in the previous Chapters, this section of the report integrates both perspectives and compares our chosen demand projection (MIT/*EIA reference case*) established in Chapter 1 - Introduction with best available estimates of supply highlighted in Chapter 2 - Demand. This analysis will measure the long term life of global uranium resources as well as shorter term shocks that might affect the nuclear fuel market as it operates today and in the near future. Detailed analysis is restricted to 2025, since projections beyond this point are subject to increasing uncertainty.

The first part of the Chapter looks at the situation over the long term. The second focuses on the short to medium term. It is helpful to consider the long term position first, since this provides important context for the short term.

4.2 Security of Current Reserves

Figure 23 displays the four projections of uranium demand based around the base case *EIA Reference* and *High* scenario for capacity growth against reserve data in the *Red Book* (red horizontal lines in Figure 23). The demand trends are cumulative for the purposes of determining the life of the current reserves.

Figure 23



If the reserve figures were accurate (i.e. if they accurately reflect the amount of conventional uranium in the ground that is mineable at a given price) then there could be some cause for concern. Our analysis suggests that at a uranium price of US$ 40 / kg, current reserves levels would last for little more than 20 years. The life of reserves increases considerably if the price of uranium over the long term increases.

However at around US$ 70 / kg, current prices are considerably higher than US$ 40 / kg and may well bring forward mine expansion and new mine plans that have been less attractive in the past.

As the most economic resources gradually deplete and demand increases, the imbalance in the market will drive prices to levels that make (previously) unattractive resources more economic. If the price of uranium were to double to more than US$ 130 / kg, there could be enough known conventional resources to last for at least another 50 years, and enough speculative resources to make uranium supplies until the end of the century.

However questions over the accuracy of reserve data were noted in Chapter 3 - Supply, and it is an issue we shall discuss later in this section.

Excluding the current supplies from secondary sources - namely stocks, MOX, etc. - we see that at a price of <US$40 / kg, there is some 1.73 Mt of uranium fuel available. Given that the current market price is roughly US$ 70 / kg), this would suggest that in the long term, the RAR reserves could provide for between more than 2 Mt of demand over the next 20 years (see Chapter 1).

- As such, if the demand trajectory were to follow our base case forecast (see the red line on Figure 23, then we would be expected RAR reserves at <$40 / kg to be exhausted by 2025 (with approximately a further ten years before RAR $40-80 / kg are exhausted).

- An increase in the utilisation rate from the base case 81% to a higher 90% (approximate to the current rate in the US) has the effect of bringing forward the depletion period to around 2023, which suggests little difference with the base case. Over a period of decades the difference between the two would be more significant.

- With a lower 70% utilisation rate the extension to the life of reserves is little more than a couple of years beyond 2025.

- It is interesting that under the highest growth rate for demand (*EIA Strong Nuclear Resurgence Scenario*), and a high utilisation rate of 90%, the depletion is brought forward to 2021. This is a strong demand scenario, but is not inconceivable.

- All of these estimates for the exhaustion of RAR <$40 / Kg occur within the 2020s. Given that reactors built today have a life expectancy of 40 to 60 years, the availability of RAR does not look promising when compared to all demand projections presented in this report.

In summary, under most demand scenarios the life of the RAR <$40 / Kg reserves are within a short horizon of between 16 and 22 years. However, this assumes that reserve data is accurate – qualifications on this point are given in Section 4.4.

4.3 Secondary Supply Issues

The range can be increased further by applying the sensitivities in Chapter 2 – Demand. MOX, for example, has the theoretical potential to reduce the demands on uranium fuel production by up to 16%. This limit exists because MOX fuel is produced from UOX reactor "waste". More waste would be required to provide more feed for MOX reprocessing; and beyond 16% there is no extra waste fuel to reprocess. In the short term, there is a sufficient supply of historical nuclear waste available, as well as contribution from HEU (see Chapter 2 - Demand).

If this potential MOX supply is phased in gradually to 16% by 2015, according to our calculations, the average share of MOX in the market over the entire forecast period averages out to roughly 12%. The life of existing reserves could be extended by some five years. However, MOX is more likely to achieve only about a third of the maximum saving over the next ten years, and so in all likelihood account for some 5% of uranium fuel supply in the future (see Chapter 2 - Demand).

4.4 Qualification and Conclusion

Chapter 3 - Supply notes that reserve data for uranium should be treated with caution. Plotting *Red Book* data for each year of publication suggests that *Reasonably Assured Reserves* and *Expected Additional Resources* (which together are known as KCR – *Known Conventional Resources*) have increased over the last 20 years – a consequence of new reserves being found and/or moved into higher confidence categories.

It is therefore inappropriate to assume that current data is an accurate reflection of physical resources. Measurement methods continue to become more sophisticated, and so it becomes easier to measure reserves at higher confidence levels. More importantly, reserves are only known with confidence following a period of exploration and investigation. As knowledge improves, new reserves can be added to reserve data.

Exploration will increase in relation to the price of uranium, and consequently more RAR and EAR reserves could be found. It is important to note that the last "boom" in exploration ended in 1979.[34] Prices have only recently climbed to a level where exploration is economic beyond the expansion of existing mines or development of nearby deposits.

Chapter 3 - Supply noted that optimists believe reserves will always increase to meet demand, and pessimists that no more major reserves will be added.[35] A more balanced conclusion is that physical constraints do exist (the amount of uranium in a high concentration is fixed) but that investment and technological advance are likely to increase current economic reserve data. As a caveat to this analysis, we note that experience in the oil sector suggests that it is possible for reserves to be overstated. At some point, a significant downgrade of resources is possible. Such uncertainty is intrinsic to reserve estimation.

In the past, the overstatement of reserves has been associated with state-owned enterprises with strategic interests in natural resources. Corporations in the private sector firms are also prone to boosting reserve figures (for example, the high profile overestimation of oil reserves by Shell in recent years). With at least half of the world's uranium production being owned by state entities (both domestically and foreign), this does not imply that half the world's reserves are exaggerated, but in a few countries this could be the case.

Table 4

Ownership of Uranium Production in 2002

	Domestic Government %	Domestic Private %	Foreign Government %	Foreign Private %	2002 production
Canada		52.0	47.0	1.0	11,607
Australia		39.1	2.9	58.0	6,854
United States					
Russian Fed	100				2,850
Kazakhstan	96.6			3.4	2,822
Namibia	3.5	96.5			2,333
Niger	32.9		38.8	28.3	3,080
Uzbekistan	100				2,300
China	100				850
Ukraine	100				1,000
South Africa		100.0			824
TOTAL	**31**	**34**	**20**	**15**	**34,520**

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[34] "Uranium - Recent Uranium Industry Developments, Exploration, Mining and Environmental Programs in the US and Overseas", *American Association of Petroleum Geologists* (Jul 2005), http://emd.aapg.org/technical_areas/uranium.cfm

[35] "Nuclear Confusion", *Fairfax Digital citing Prospect Magazine* (Jul 2005), http://afr.com/articles/2005/06/23/1119321845502.html

Taking these factors into account, the WNA is firm in its belief that even a significant increase in the use of nuclear power will not cause a shortage of nuclear fuel for several hundred years.

The MIT are similarly optimistic, concluding that: "world-wide supply of uranium ore is sufficient to fuel the deployment of 1000 reactors over the next half century, and to maintain this level of deployment over a 40 year lifetime of this fleet". This leads them to recommend focusing on a once-through uranium fuel cycle - which requires more uranium than using MOX (see Chapter 2 - Demand) but has other potential benefits, such as non-proliferation and lower cost.

OECD/IAEA follow the same line: the *Red Book* concludes that the volume of resources are not a serious concern over the 21st Century:

> "*Do sufficient resources exist to support a significant growth in nuclear capacity for electricity generation or other uses in the long term? Known conventional resources are sufficient for several decades at current usage rates. Exploitation of undiscovered conventional resources could increase this to several hundreds of years, though significant exploration and development effort would be required to move these resources to more definitive categories. However, since the geographical coverage of uranium exploration is not yet complete worldwide there remains the potential for discovery of new resources that could be exploited.*"

The industry is thus confident that sufficient uranium resources are available to fuel another century of nuclear power.

Even with the EIA strong nuclear revival scenario and a high 90% utilisation rate (compared with 81% in the base case), known uranium resources could last until the end of the century - assuming KCR resources continue to be booked over the next 20 to 30 years.

Nevertheless, imprecision in reserve data remains high, and it is possible that speculative resources in particular, do not fully materialise at an economic cost of extraction. In calculating the expected lifetime of uranium resources, uncertainty over reserve estimates is likely to be more significant than uncertainty over cumulative demand, despite the significant range given by plausible demand projections.

One factor we have not assessed in this report is the significance of price. The price can be expected to rise as primary production begins to respond to strong demand. Given a very high price of uranium (<$130 / kg) available resources are large – the question is whether nuclear utilities are able to absorb such a further doubling of uranium prices.

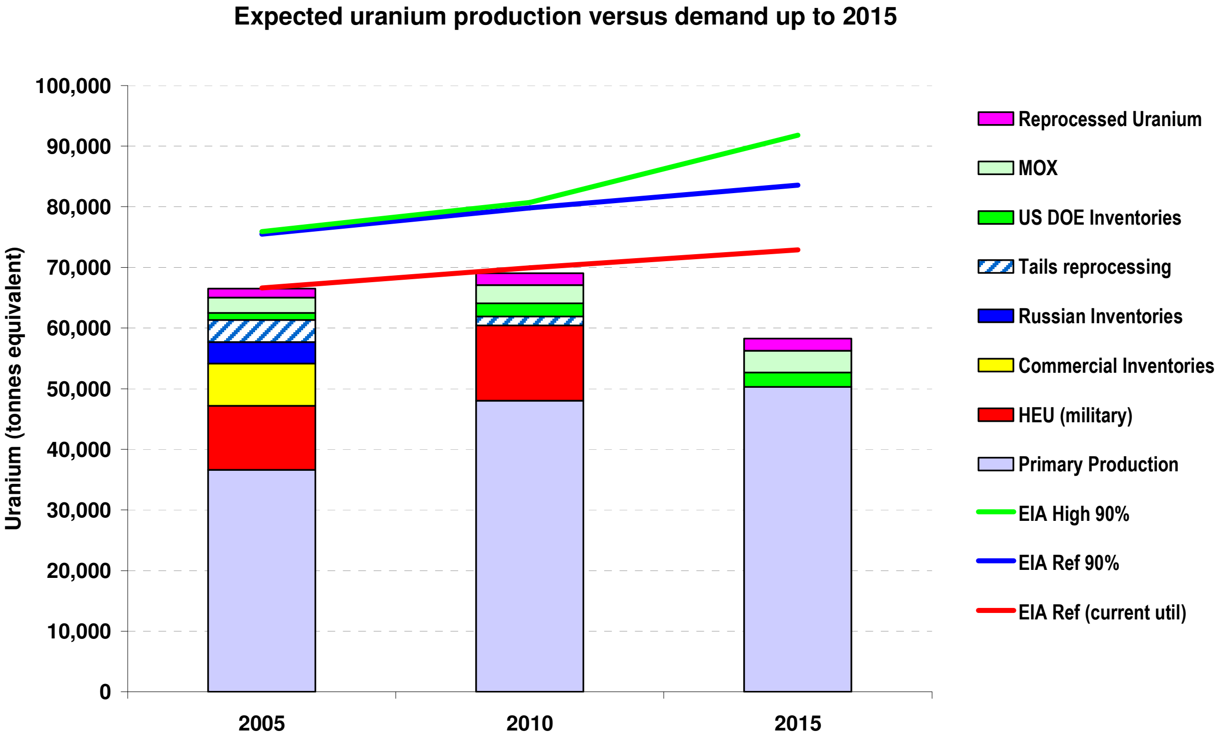
4.5 Resources in the Short to Medium Term

In the short term supply is limited by the capacity to produce from existing (or planned) sites. Further downstream, the capacity to convert and then to enrich uranium (as well as transport it) are all important links in the supply chain. As described in Chapter 3 - Supply, this picture is complicated by the contribution of secondary supply sources, which will continue to be significant until around 2020.

Figure 24 compares the short term supply projections provided by Dzhakishev (see Chapter 3 - Supply) with the EIA reference scenario (Chapter 2 - Demand). During this forecast period the uncertainties can be better defined. For example, the expected production of particular mines can be considered.

It is clear from Figure 24 that supply will not fully meet demand over the next decade. In fact, a supply shortfall can be expected for each year until at least 2015, with the shortfall increasing over the period. *Red Book* projections for demand are slightly higher than ours for the period 2005 to 2010. Our reference estimates 66,600 tonnes in 2005, whereas the *Red Book* suggests 70,600 tonnes. Dzhakishev uses a demand projection closer to ours, at 66,500 for 2005.

Figure 24



The extent of any shortfall is clearly determined by the assumptions on both the supply and the demand side. The blue line indicates what would happen to demand in the event of an increase in utilisation to 90%: annual demand increases by around 10,000 tonnes. This is unlikely to occur overnight, but any increase in utilisation will naturally increase the supply gap even if the trend occurred over a few years, this remains significant.

The green line is taken from the *EIA strong nuclear revival scenario*, and reflects the possibility of extra capacity. Capacity assumptions become more significant relative to utilisation assumptions as the projections move into the future.

By 2015, the shortfall to the *EIA reference* demand scenario has increased to 14,000 tonnes per year. This is partly due to an increase in demand, but more significant is the lack of uranium derived from the US-Russian HEU-II agreement (see Chapter 3 - Supply). This supply may or may not occur after 2013, and Dzhakishev chose to exclude it in this case. If we assume that HEU continues at 2010 levels, supply continues to be around 2,000 tonnes below reference scenario demand by 2015.

To place these figures in context, the world’s largest mine, McArthur River, produced 7,200 tonnes per year in 2004, around 11% of total world supply (world = 67,000 tonnes).

A force majeure shutdown of McArthur River would therefore lead to potential 11% drop in annual supply. The major new mine Cigar Lake is expected to produce around 6000 - 8,000 tonnes per year by 2015. It is due to start operation in 2007 and a delay here would have significance to the world market. Other major expected additions include the Jabiluka and Honeymoon mines in Australia.

Dzhakishev has used relatively positive assumptions about Cigar Lake, Jabiluka and Honeymoon in his primary production model – he notes that his assumptions are more positive than IAEA figures.

Since a shortfall is predicted from *expected* supply, it is reasonable to assume that a more serious supply problem could occur resulting from events such as:

a) A delay in the introduction of new mines. There are concerns over possible delays at Cigar Lake (2007), Jabiluka (2011), and Honeymoon largely due to low uranium prices in the past.[36]

b) A problem at one or more existing mines (McArthur flooded in 2004, for example, taking it out of action for three months. A six month delay had been expected).[37]

c) Problems at conversion and enrichment plant (Honeywell's major Metropolis conversion plant had an outage in 2004).

d) The end of HEU supplies in 2013.

e) Rapid (and unexpected) demand increases, particularly as a result of a leap in utilisation rates of power generators resulting from utilities responding to market factors such as higher oil prices, or a failure of fossil or renewable power generators too name but a few.

Taken together, this analysis suggests an uncomfortably high level of risk to uranium supply security over the short to medium term. This is consistent with recent analysis in the literature.

For example, the IAEA *Red Book* expects a shortfall of 10,000 tonnes pa (high demand scenario) and 20,000 tonnes pa (low demand scenario) to exist by 2020 even assuming all planned and prospective supplies materialise. The Asia Pacific Foundation of Canada has predicted

> *"a 45,000 tonne shortage of uranium in the next decade, largely because of growing Chinese demand for the metal".*[38]

The president of Nuclear Resources International, a leading consultancy, states that

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[36] ”Teetering on the Brink?”, Connor M, *WNA Annual Symposium* (Sep 2003) http://www.world-nuclear.org/sym/2003/pdf/connor.pdf

[37] ”The Macarthur River Mine Flood”, *ITT Flygt* (2003), http://www.ittflygt.ca/Site/En/Pumptalk/Casestories/TheMcArthurRivermineflood.asp

[38] ”Uranium Shortage Poses Threat”, Jameson A, The Times (August 2005), http://business.timesonline.co.uk/article/0,,9069-1735134,00.html

> *"regardless of which demand forecast you prefer to use, a shortfall of uranium supplies is imminent".*[39] *Moreover, "with only 55% of supply [to the west] identified ten years out (in an industry where ten years is tomorrow), the message is that the viability of nuclear industry generation is, itself, seriously endangered… Removing just four currently expected key new supplies leads to a market basically in chaos. The market absolutely must have these four expected supplies, and more new ones in addition."*[40]

To some extent, these commentators are trying to stimulate the market to increase investment (and assuage the "crisis"). At the same time as indicating the risks, they also argue that – assuming considerable effort is made – the uranium market will respond in time to prevent a supply shortfall that would impact directly on nuclear generation.

On the other hand, the fact that a "chaos" scenario is plausible is a strong indication that risks to security are significant. Even assuming the market responds, the short term situation is more complex than "stimulate investment and production will increase". Uranium exploration is a high-risk business and exploration does not always lead to discovery and production:

> *"Only about one in one thousand projects progress to advanced exploration and development. Following discovery of a deposit that may be feasible to develop, a further period prior to production is required for development. Development timing is dependent on the nature of the mining operation, the regulatory requirements of the jurisdiction in which the deposit is located and, of course, the market price for uranium that controls the fundamental economic feasibility of development."*

It can therefore take anything from a few years to decades to bring a newly found reserve online. In the short term, it is quite possible that expected additions might not materialise, in Australia, progress on the Honeymoon was delayed in order to wait for higher uranium prices. With a cash operating cost of roughly US$ 25 / kg, it is quite likely that the current price of US$ 70 / kg could stimulate the development.

There is also no guarantee that an agreement between the US and Russia for HEU-II will go ahead, which would affect supply after 2013. In these same negotiations, the Iran issue is particularly prominent – with the increase in diplomatic tension between the US and Russia over Iran, the risk of this supply source not occurring has risen further although the potential contribution Iran would make to the world market is negligible.

4.6 Demand Side Response

Nuclear utilities will naturally try to avoid a situation where they are forced to limit generation in order to conserve fuel. The Euratom Supply Agency is trying to persuade utilities in the EU Member States to increase their inventories to help them manage a supply shortfall.

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[39] "Teetering on the Brink", Connor M, WNA Annual Symposium, (Sep 2003), http://www.world-nuclear.org/sym/2003/pdf/connor.pdf

[40] "Teetering on the Brink", Connor M, *WNA Annual Symposium* (Sep 2003), http://www.world-nuclear.org/sym/2003/pdf/connor.pdf - The four sources are Honeymoon, Jabiluka, Cigar Lake and Russian HEU-II

An interesting demand side response to supply shortage (and high prices) occurs when utilities "start to order enrichment with lower tails assays to conserve inventories and extend contracted natural uranium supplies".[41] Most of the supply to the EU utilities continues to take place under long term contracts.[42] Moving from 0.30% tails to 0.25% tails reduces uranium demand by around 10%, as is described in Chapter 2 – Demand.

However, "the degree to which enrichment can be substituted for uranium is limited by the amount of economic enrichment capacity that is available".[43] It takes greater capacity to achieve a higher enrichment which then results in lower tails – therefore tails cannot be reduced further if the enrichment capacity is not in place.

4.7 Enrichment

Enrichment capacity is currently sufficient. As noted in Chapter 3 - Supply, the EU capacity is greater than it requires. However, after several decades of excess capacity in the global market, there is now concern that a shortfall in enrichment may also occur if the expected future growth in demand is realised. Combs suggests that 30% growth in enrichment capacity will be required by 2020 under the *WNA low scenario* (which broadly equates to the *EIA reference scenario*).[44] Again, this is achievable, but will require significant investment in the short term. Since it may be a challenge to meet enrichment capacity, the possible savings from stripping tails to 0.25% (for example) may not be fully realised.

4.8 Fuel Conversion

Conversion, which has previously not been a problem, is now a concern for the ESA. It notes that most of the capacity will be available in North America, which may require the transportation of large quantities of UF_6 to the enrichment plants located in Europe.[45]

4.9 A Failing Market?

It may well be the case that, as analysts hope and expect, a crisis can be averted over the next decade. However, the present situation does raise serious issues related to the security of uranium supply. The obvious question is: why did uranium production not rise in anticipation of a widely predicted shortfall? A cogent answer to this has been provided by Jeff Combs[46]:

> "*There has been considerable discussion recently about a production or supply gap in uranium. Discussing the existence of such a gap really doesn't make any sense without introducing the concept of market failure. This is because the gap problem can be seen as directly related to the disconnect between the current price and a future price that would result in the requisite amount of supply.*

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[41] "Fueling the Future, A New Paradigm - Assuring Uranium Supplies in an Abnormal Market", Combs J, WNA (Sep 2004), http://www.world-nuclear.org/sym/2004/pdf/combs.pdf; Combs also estimates the saving at about 10%

[42] "Annual Report", *Euratom Supply Agency* (2002), http://europa.eu.int/comm/euratom/ar/ar2002.pdf

[43] "Fueling the Future, A New Paradigm - Assuring Uranium Supplies in an Abnormal Market", Combs J, *WNA* (Sep 2004), http://www.world-nuclear.org/sym/2004/pdf/combs.pdf

[44] "Fueling the Future, A New Paradigm - Assuring Uranium Supplies in an Abnormal Market", Combs J, *WNA* (Sep 2004), http://www.world-nuclear.org/sym/2004/pdf/combs.pdf

[45] Annual Report, *Euratom Supply Agency* (2002), http://europa.eu.int/comm/euratom/ar/ar2002.pdf

[46] Leading uranium analyst and president of the Ux Consulting Company

> *Market failure is also the reason why it is so difficult for market participants to believe that there may be a supply gap problem. The reasoning goes that if prices are low, then uranium supplies must be plentiful, and if they're plentiful, there shouldn't be any problem meeting demand in the future at prices not too different from today's.*
>
> *Compounding the problem is the fact that we have all heard for a number of years about the supply or production gap and the high prices that it would bring. When the higher prices suggested by the gap projection didn't materialize, people became complacent. In hindsight, there were considerable inventories to be worked off. As prices fell and stayed low, utilities opted to hold fewer inventories, so even more inventories were worked off, further depressing price and production.*
>
> *Of course, if prices didn't adequately reflect the scarcity of supplies (i.e. the market was in failure), then utilities and producers were making incorrect decisions. What is becoming clearer than ever is that spot price is giving us a different message than the one we get from a simple examination of production versus requirements. The seriousness of market failure should not be underestimated. It's like the market's gas gauge is broken. The gauge (price) suggests the tank is full or nearly so (supplies are plentiful), when in reality it's much closer to being empty (supplies are scarce). Having the correct price signals is crucial to providing adequate supplies in the future."* [47]

Since Combs wrote this in 2004, the price of uranium has continued to rise. The market appears to be responding to the warnings, if belatedly. As primary production comes to dominate supplies in the next decade, the hope in the nuclear industry must be that the responsiveness of primary production to demand will continue to improve. The major producers, enrichers and transporters will provide most of the effort and investment. However, it is in the nature of uranium trade that government policy will continue to be highly influential.

The politics of uranium trade and security are assessed in Chapter 5 - The Politics of International Uranium Trade. The analysis builds upon the analysis in Chapters 2 to 4.

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[47] “Fueling the Future, A New Paradigm - Assuring Uranium Supplies in an Abnormal Market”, Combs J, *WNA* (Sep 2004), http://www.world-nuclear.org/sym/2004/pdf/combs.pdf

5 The Politics of International Uranium Trade

5.1 Politics and Trade

Due to safety, security and strategic considerations, supply of uranium is not an open market. Purchases are made through state organisations (all supplies in the EU are purchased through the Euratom Supply Agency - ESA) and specific trade agreements exist between the major players in the market. Many of the principles governing the debate are contained in the *Non-Proliferation Treaty* and the *Nuclear Suppliers Group* (NSG).

The NSG specifically requires that "Suppliers should have in place legal measures to ensure the effective implementation of the Guidelines, including export licensing regulations, enforcement measures, and penalties for violations". 44 countries are signatories, including Canada, Australia, Kazakhstan, the US, the UK, China, Russia, South Korea and Japan.

Beyond non-proliferation concerns, trade disputes have also developed along (alleged) economic grounds. Of particular significance is the US Department of Trade's conclusion in 1992, that uranium from six newly independent former Soviet republics was being sold in the USA at "less than fair value". These republics were Kazakhstan, Kyrgyzstan, Russia, Tajikistan, Ukraine and Uzbekistan. As a result, the Department of Trade set a preliminary anti-dumping import tariff of 115.82% on uranium from each of the newly-independent republics. Import quotas were also implemented and the negotiations are ongoing.

Another major issue is the trade regimes applied by potential importers of Western-origin tails exported to Russia for re-enrichment. For example, the US considers that such material is subject to the same import restrictions as Russian material. Among other restrictions, it is thus subject to the provisions of the US-Russia Suspension Agreement (a consequence of the dispute described above). Since many emerging demand regions are non-OECD, producer-supplier relationships are evolving relatively quickly. Although the economics of uranium trade are clearly an important driver, geopolitical considerations are often focused on non-proliferation; naturally this places emphasis on activities in or with non-nuclear weapons states. The position Country A assumes with regards Iran, for example, may directly or indirectly determine whether exports to Country A are considered appropriate by the US and the EU.

The companies with ownership of major producing centres are typically either national state companies or trans-national private firms. For example, in Kazakhstan production is typically the result of joint ventures between Kazakhatomprom and Cameco – a Canadian company which is a major global producer. Table 5 *Key producer – consumer relationships* summarises some of the key producer-consumer relationships. The analysis is generally focused at state level (at the location of production or demand) rather than on the "nationality" of producing firms. A general observation is that market power rests with producing countries, who – particularly in the case of Canada, the US and Australia – are willing to restrict sales where non-proliferation concerns emerge. While there may be discussion and even disagreement between OECD states, more serious issues arise almost exclusively between the major OECD suppliers (and other NSG signatories) and the FSU, China and India[48].

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[48] It is interesting that India has only recently been seen as an appropriate importer of uranium – and this is yet to be agreed at the Nuclear Suppliers Group. The US has recently shifted its position, and is now promoting the idea of exports to India.

Table 5 Key producer – consumer relationships

Canadian export policy is positive towards China. A recent official statement "There is no reason why any further sales of Canadian-origin uranium couldn't take place, provided that China would consider the transaction likewise subject to our peaceful-use provisions" (Platts, 2005)
Canada currently will not export to India A bilateral nuclear cooperation agreement with India was nullified by Canada after India tested a nuclear explosive device in 1974, which used plutonium separated from a Canadian-supplied heavy water research reactor. The Nuclear Suppliers Group was established in reaction to the incident. No Canadian uranium will be sold to India unless Canadian policy is officially amended. (Platts, 2005)
Australia is working towards formal agreement with China Australian Minister of Foreign Affairs Alexander Downer announced in August 2005 that Australia will formally commence negotiations on a nuclear cooperation agreement with China. This will establish safeguards arrangements to ensure Australian uranium supplied to China is used exclusively for peaceful purposes. Australia also has a safeguards agreement with the US covering the supply of Australian uranium to Taiwan. (Platts, 2005; Australian Dept Foreign Affairs & Trade, 2005[49])
Australia does not permit the use of its uranium by Russia. Australia has an agreement with Russia but that agreement only covers the processing of Australian uranium in Russia on behalf of other partner countries.
Russia has supplied India with uranium in defiance of the NSG This has brought a strong response from the US. The State Department made the following comment in February 2001: "We deeply regret that the Russian Federation has shipped nuclear fuel to the Tarapur power reactors in India in violation of Russia's non-proliferation commitments. As a member of the Nuclear Suppliers Group, Russia is committed not to engage in nuclear cooperation with any country that does not have comprehensive International Atomic Energy Agency (IAEA) safeguards on all its nuclear facilities. Although India's Tarapur reactors are under International Atomic Energy Agency safeguards, India does not have such safeguards on all of its facilities and is indeed pursuing a nuclear weapons program… We join other nuclear suppliers in calling on Russia to cancel this supply arrangement and live up to its non-proliferation obligations". (US State Department, 2001[50])

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[49] "Nuclear Non-Proliferation and Arms Control, Nuclear Exports and Safeguards, Australia's Uranium Exports Policy", *The Australian Government Department of Foreign Affairs and Trade* (Oct 2005), http://www.dfat.gov.au/security/aus_uran_exp_policy.html

[50] "Russian shipment of low enriched uranium fuel to India", *US Department of State,* (Feb 2001), http://www.usembassy.it/file2001_02/alia/a1021910.htm

The US is seeking to normalise uranium trade with India.

A change in US policy led, in July 2005, to the announcement by President Bush that he would ask Congress to modify US law and permit the US to supply India with nuclear materials and technologies to produce nuclear energy. He also said he would ask foreign governments to adjust similar international restrictions (Arms Control Association, 2005[51]) France, Russia, and the UK have welcomed the move but - since the NSG operates by consensus - more support will probably be needed. Australia has yet to declare whether it is willing to export to India.

US-Russia HEU agreement

It is uncertain whether this will be extended after 2013 (Connor, 2004)[52]. Under the program, the Russians are taking 500 mega tonnes of bomb-grade uranium from nuclear weapons and converting that uranium into low-enriched uranium (LEU), which can be used by commercial reactors.

US-Russia Suspension Agreement

In 1992 the US Department of Trade established an anti-dumping tariff on Kazakhstan, Kyrgyzstan, Russia, Tajikistan, Ukraine and Uzbekistan. Subsequently the tariff was removed in favour of a price-related quota (this second agreement is known as the "Suspension Agreement"). (WNA, 2004)[53]

Euratom Supply Agency (ESA)

Within the EU, Euratom Supply Agency and the European Commission pursue the objective of long term security of supply through *a reasonable diversification of supply sources and the avoidance of excessive dependency on any one supply source.* In effect, this imposes a 20% limit to Russian imports, although the policy will also apply to Kazakhstan. (ESA, 2005)[54]

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[51] "US-India nuclear prospects murky", *Arms Control Association* (Oct 2005), http://www.armscontrol.org/act/2005_10/OCT-USIndiaMurky.asp

[52] "Teetering on the Brink?", Connor M, *WNA Annual Symposium* (Sep 2003), http://www.world-nuclear.org/sym/2003/pdf/connor.pdf

[53] WNA Trade Briefing – "Uranium Imports to the USA from CIS countries", *WNA*, http://www.world-nuclear.org/trade_issues/tbriefings/uiusa/

[54] http://europa.eu.int/comm/euratom/index_en.html

5.2 Implications for Government

Uranium supply and demand have many implications for government policy, and is at the same time sensitive to policy. This section describes the various policy drivers and tools, and should be seen in the context of the expected short term supply shortfall.

Government can influence uranium production, investment activity and trade with various policy measures. For example, by releasing stocks; adjusting tax; changing planning and environmental regulations; advertisement of new concessions (areas of land available for production); education and training; and via the trade regime (see Chapter 3 - supply).

A key factor is that governments are typically more sensitive to security and strategic considerations than they are to creating a level playing field for the uranium market.

For instance, in the 1980s governments sold a large amount of their inventories, much of it former weapons material. This had the effect of pushing price to very low levels as well as suppressing production and exploration efforts.[55] The significant upside to this activity was that considerable amounts of weapons-grade material were destroyed.

Likewise, a popular foreign policy strategy is to offer supply guarantees of (enriched) uranium fuel to countries that agree to forgo any plans to enrich uranium themselves (since without enrichment, concerns over non-proliferation are much reduced). This naturally has large implications for the enrichment market, not least where plant is situated.

Consumer states use policy and diplomacy to ensure their own supply is secure. In terms of primary production this is more difficult since for most it is inevitable that supply will be imported. An example of policy in this direction is that, until recently, France preferred to source uranium from its former colonies in Africa.[56]

Consumer states clearly have greater influence over the siting of conversion and enrichment capacity, and often support these industries domestically (see following section).

Producing states understand the strategic importance of their reserves. The benefits are clear in terms of increasing the international significance and power of the state, and in the economic gains (the latter perhaps particularly significant for transition states such as Kazakhstan). Australia is described as having increased its recognition of the strategic value of uranium in recent years.[57]

Since all major consumer and (especially) producer governments have significant influence over uranium trade, it follows that this is an area that requires active foreign policy. It is also the case that non-proliferation concerns in the west and elsewhere determine the pattern and terms of trade. Conditions of supply typically refer to security over nuclear materials, sites and transport; enrichment - considered by the west to be particularly unwelcome in non-nuclear (weapons) states; and to attitudes to nuclear activities in other states (the

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[55] "Fuelling the Future, A New Paradigm - Assuring Uranium Supplies in an Abnormal Market", Combs J, *WNA* (Sep 2004), http://www.world-nuclear.org/sym/2004/pdf/combs.pdf

[56] "The French Desire for Uranium And its Effects on French Foreign Policy in Africa", Pederson N R, *University of Illinois* (May 2000), http://www.acdis.uiuc.edu/Research/OPs/Pederson/PedersonOP.pdf ; France has been more active than most in uranium foreign policy

[57] "The Strategic Importance of Australia's Uranium Resources", Stephens A J, *Arafura Resources NL* (May 2005), http://www.aph.gov.au/house/committee/isr/uranium/subs/sub22.pdf

differences between Russia and the US with regards Iran currently providing the best example).

As in many sectors, policy can also be influenced by industry lobbying over investment and employment. Alleged "dumping" of under-priced uranium led the US to impose trade sanctions on the FSU in 1992 in order to protect domestic industry.

In the context of these various drivers, some of which are among the top priorities for foreign policy in many countries, it is difficult to criticise government intervention in uranium markets *per se.* The question is how best to achieve strategic and security goals without causing unnecessary disruption to the market. For example, governments could make an important contribution by reducing policy uncertainty. Uncertainty often has a negative impact on investment - particularly when it appears that the government is in a position to step in with extra supplies in the event of a serious shortage.

Combs suggests the following measures to reduce uncertainty and stimulate investment:

- publish data on commercial requirements, contracting, prices, and inventories
- publish data on state inventories and disposition plans
- open up land for exploration, including to foreign investors.

5.3 Uranium Trade and the EU

EU Member States typically choose not to make independent contributions to the various issues related to uranium trade. Instead they work within the Euratom Supply Agency (ESA), the European Commission and other initiatives such as the EU-Russia Dialogue. Germany, France and the UK have recently chosen to combine their foreign policy approach on Iran.

The Euratom Supply Agency and the European Commission "pursue the objective of long term security of supply through a reasonable diversification of supply sources and the avoidance of excessive dependency on any one supply source, and ensure that in a context of fair trade, the viability of the nuclear fuel cycle industry is maintained". The policy behind these objectives is contained in the Corfu Declaration of 1994 – a declaration which remains unpublished (see below).

The Euratom Treaty of 1960 gives the Euratom Supply Agency the right of option to acquire ores, source materials and special fissile materials produced in the EU and an exclusive right to conclude contracts for the supply of such materials from inside the Community or from outside. In order to be valid under Community law, supply contracts must be submitted to the Supply Agency for conclusion.[58]

Whereas primary uranium production in the EU is very small in global terms, the Union's enrichment services are almost self-sufficient (80%). The enrichment market is subject to considerable intervention by the Euratom Supply Agency and the European Commission.

In a review of the proposed merger between European firms Areva (France) and Urenco (Netherlands, UK, Germany), the Commission found that the two firms already had a combined share in the EU market of 70% - 90% and that Tenex – a Russian firm – could not apply serious competitive pressure since "It is generally agreed by the parties, third parties

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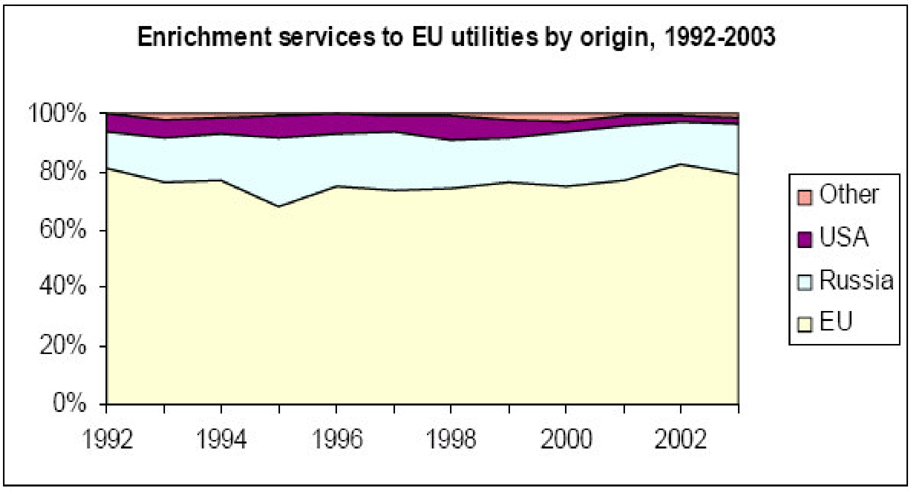
[58] Mission Statement, *Euratom Supply Agency* (Apr 2005), http://europa.eu.int/comm/euratom/mission_en.html

and Euratom Supply Agency that the Corfu Declaration restricts the supply of Russian material to a share of 20% of the Community market". While the Commission does not support a further concentration of the market through the merger, it does not suggest that the (de facto) quota is inappropriate.

Figure 25



The US has begun to formally question EU policy, although discussions are not excessively strained. In November 2004, the US submitted several questions regarding enriched uranium to the European Commission at the WTO with the following context:

> *"Since 1992, the EU has maintained strict quantitative restrictions on imports of natural and enriched uranium to protect its domestic producers. Since 1994, import restrictions have been applied in accordance with the terms of a never published declaration, the Corfu Declaration, which reportedly imposes explicit quotas for imports of both natural and enriched uranium… Clearly these restrictions have had a negative impact on import suppliers and we believe it is time to provide more information on these restrictions."*[59]

Despite such attempts to gain improved market access, it is clear that a level of market intervention is widely accepted. The limited strength of language in the extract above is indicative; the US does not explicitly question the EU's right to impose quotas, asking only that the policy guiding intervention is made public. This is in contrast to the very strong language used by the US when discussing the non-proliferation aspects of trade (see Table 5 *Key producer – consumer relationships* earlier in section).

Overcapacity has existed in the global civilian enrichment market since the 1970s, particularly in the FSU. [60] Assuming that an 80% internal supply of enriched uranium is maintained (see Figure 25), EU utilities can have a good degree of confidence over enriched uranium supply security. Some concern does exist about future capacity. Russian re-enrichment is an important supply source as described earlier, and uncertainty over future US enrichment capacity is included on ESA's *top 10 risks* at the end of Chapter 3 - Supply.

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[59] Questions from the United States to the European Communities, "Restrictions on Sales of Uranium" (Nov 2004).

[60] Trends in Enrichment, Davies S, paper presented at *World Nuclear Fuel Market* (Jun 2000), http://www.wnfm.com/2000proceedings/SashiDavies-sp.pdf.

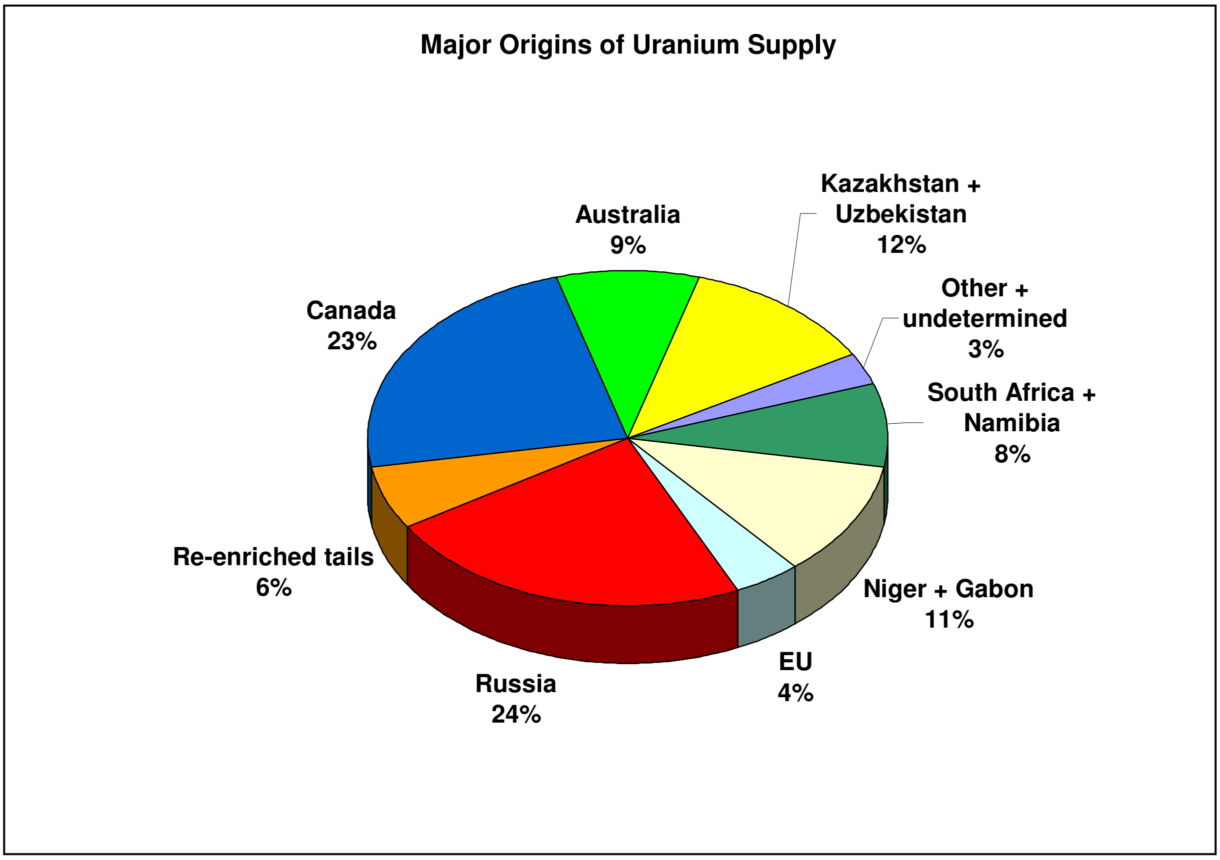
However, uranium mining probably deserves greater emphasis in a short to medium term security of supply analysis; as noted in Chapter 4 - Analysis of Resource Availability where a shortfall in uranium supply is predicted over the next ten years.

5.4 Implications of Supply Analysis for the EU

As can be seen from Figure 26, the major origin countries for supply of uranium fuel are Canada (23%), Russia (22%), Niger and Gabon (11%) and Kazakhstan and Uzbekistan (12%).

In the medium to long term, a key strategic concern for EU uranium supply security is the dependence on non-OECD nations. Russia – because of its high contribution and its unique position in enrichment and HEU – is particularly important. Kazakhstan is also very important but for the reason that it is seeking to become the largest global primary producer. These two countries have therefore been selected for particular consideration.

Figure 26



As already noted, the Corfu Declaration imposes a maximum of 20% on the Russian contribution – although it is not clear why the data shows the share to be above this as shown in Figure 26. Since several EU accession states have links with Russia – and given the growing global shortage of uranium - there have been discussions about increasing the 20% "limit".

Negotiations over uranium continue as part of the EU-Russia energy dialogue. The following quote is taken from the second progress report of the Dialogue in 2002 (a joint statement by Brussels and Moscow):

> *We recognise that, over the last decade, the question of the trade in nuclear materials has been a delicate issue between the EU and Russia. The European Commission stresses [that] in the light of possible increasing supplies available from Russia, the EURATOM Supply Agency has applied a policy of ensuring a diversification of the sources of supply of natural and enriched uranium through quantitative limits to imports. Russia stresses that qualitative limitations in trade of nuclear materials between Russia and the EU are discriminatory.*

The Russian situation is complicated by agreements with (and financed by) the US over blending down of HEU and trade of enriched and re-enriched material. This is could dramatically affect Russian contribution to the EU, since agreements have not been finalised with the US for after 2012.

Kazakhstan – a Possible Market Leader?

Along with Russia, Kazakhstan is probably the area of greatest strategic interest for the EU. Kazakhstan has ambition to become the leading producer of uranium by 2010, not surprising given its large economic reserves (see Chapter 2 - Demand). In 2000 it produced 1,870 tonnes, then 2,822 in 2002. Latest figures put the country at 3,714 tonnes since 2003.[61] At the rate of 1000 tonnes additional production per year, the country will begin to challenge Canada for top position by the end of the decade.

In contrast to many of the so-called Stans, Kazakhstan it is generally considered a success story. For the last three years is has experienced GDP growth of around 9%, largely driven by its fossil fuel production. The National Committee on American Foreign Policy note that "*it is predominantly secular and pro-American, harbors few extremists, and does not share borders with Iran and Afghanistan*".[62] However, the country is not without investment risks. Corruption and nepotism "are endemic" and there have been recent suggestions of a lack of national identity. Such issues have led to concerns over the medium to long-term stability of the country.[62]

Of more specific concern is government foreign investment policy: according to the CIA, this "aims to reduce the influence of foreign investment and foreign personnel; the government has engaged in several disputes with foreign oil companies over the terms of production agreements, and tensions continue".[63] However, at present Kazakhatomprom continues to enthusiastically offer possible joint ventures.[64]

These concerns are primarily related to the ability of Kazakhstan to raise its production output – due to the current political and economic stability, there is less immediate concern over the possibility of an abrupt stop to supplies (either as a foreign policy tool or resulting

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[61] China's Energy Demands Fueling Canada's Uranium Exploration in Asia, *Asia Pacific Bulletin, number 210* (May 2005), http://www.asiapacificbusiness.ca/apbn/pdfs/bulletin210.pdf

[62] Stability in Central Asia: Engaging Kazakhstan, Rywkin M, *National Committee on American Foreign Policy* (May 2005), http://www.ncafp.org/projects/RussiaCentralAsia/may05_kazahkstan.htm;

[63] World Factbook - Kazakhstan, *CIA* (Oct 2005), http://www.cia.gov/cia/publications/factbook/geos/kz.html

[64] Uranium production in Kazakhstan as a potential source for covering the world uranium shortage, Dzhakishev M, *WNA Annual Symposium* (Sep 2004), http://www.world-nuclear.org/sym/2004/pdf/dzhakishev.pdf

from internal instability). Nevertheless, there is a strategic need to monitor the situation over the medium term.

Of potentially greater significance to supplies is the possibility of regional instability, which – amongst other things – could lead to a loss of Kazakh investment. A more specific concern is that transport links are poor and could be easily disrupted.[65]

Given that supplies are already short, an end to supply from any of these countries would be serious. An immediate termination of trade is clearly unlikely, but the possibility exists via natural disaster or political upheaval. The analysis above focuses on Russia and Kazakhstan, both of which are expected to be very significant suppliers over the next decade and beyond. In both cases, significant risks exist - although they are different in each case. The situations in Niger, Gabon and Namibia also warrant monitoring, although production levels are either stable or declining in each case.

It is conceivable that a non-OECD producer might, at some point, restrict supplies to OECD countries on strategic or political grounds. For several reasons, this would not have an impact of the magnitude of the OPEC action in 1973 - a longer time-period of stocks exist; transport would not be affected; oil is far more important to most economies than uranium; and the largest uranium producer is currently Canada, with several other OECD countries making major contributions. However, given a particularly tight supply situation, a relatively low percentage loss of supply might still cause a serious problem for the nuclear generation industry.

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[65] Stability in Central Asia: Engaging Kazakhstan. A Report (with Policy Recommendations) on US Interests in Central Asia and US-Kazakhstan Relations, *National Committee on American Foreign Policy* (May 2005), http://www.ncafp.org/projects/RussiaCentralAsia/may05_kazahkstan.htm

GLOSSARY

A

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

B

Background radiation: The naturally-occurring ionising radiation which every person is exposed to, arising from the earth's crust (including radon) and from cosmic radiation.

Base load: That part of electricity demand which is continuous, and does not vary over a 24-hour period. Approximately equivalent to the minimum daily load.

Boiling water reactor (BWR): A common type of light water reactor (LWR), where water is allowed to boil in the core thus generating steam directly in the reactor vessel. (cf PWR)

Breed: To form fissile nuclei, usually as a result of neutron capture, possibly followed by radioactive decay.

Breeder reactor: see Fast Breeder Reactor and Fast Neutron Reactor.

Burn-up: The amount of thermal energy released per unit mass of fuel (not the same as the thermal efficiency of the power generator). Reflects the efficient use of U-235 by the reactor to produce thermal energy. High burn-up reduces demand for uranium fuel at the reactor, but can lead to increased uranium demand during enrichment. It is measured in GWd / MTIHM, or abbreviated to GWd / t.

C

Calandria: (in a CANDU reactor) A cylindrical reactor vessel which contains the heavy water moderator. It is penetrated from end to end by hundreds of calandria tubes which accommodate the pressure tubes containing the fuel and coolant.

CANDU: Canadian deuterium uranium reactor, moderated and (usually) cooled by heavy water. CANDU requires un-enrichment uranium only therefore eliminating a major stage of the fuel process.

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

Central Intelligence Agency (CIA): US Government publishers of country factbooks.

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

Concentrate: See Uranium oxide concentrate (U_3O_8).

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

Conversion: Chemical process turning U_3O_8 into UF_6 preparatory to enrichment.

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

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

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

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

D

Decay: Disintegration of atomic nuclei resulting in the emission of alpha or beta particles (usually with gamma radiation). Also the exponential decrease in radioactivity of a material as nuclear disintegrations take place and more stable nuclei are formed.

Decommissioning: Removal of a facility (e.g. reactor) from service, also the subsequent actions of safe storage, dismantling and making the site available for unrestricted use.

Depleted uranium: Uranium having less than the natural 0.7% U-235. As a by-product of enrichment in the fuel cycle it generally has 0.25-0.30% U-235, the rest being U-238. Can be blended with highly-enriched uranium (e.g. from weapons) to make reactor fuel.

Deuterium: "Heavy hydrogen", a stable isotope having one proton and one neutron in the nucleus. It occurs in nature as 1 atom to 6500 atoms of normal hydrogen, (Hydrogen atoms contain one proton and no neutrons).

E

EAR (I) - Estimated Additional Resources (I): Based on direct geological evidence, in extensions of well-explored deposits, or in deposits in which geological continuity has been established. However, the lack of detailed specific data prevents these resources from being classified RAR.

Energy Information Administration (EIA): Part of the United States Department of Energy. Publishes the International Energy Outlook, last published July 2005.

Enriched uranium: Uranium in which the proportion of U-235 (to U-238) has been increased above the natural 0.7%. Reactor-grade uranium is usually enriched to about 3.5% U-235, weapons-grade uranium is more than 90% U-235.

Enrichment: Physical process of increasing the proportion of U-235 to U-238.

ESA: Euratom Supply Agency

F

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

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

Fertile (of an isotope): Capable of becoming fissile, by capturing neutrons, possibly followed by radioactive decay; e.g. U-238, Pu-240.

Fissile (of an isotope): Capable of capturing a slow (thermal) neutron and undergoing nuclear fission, e.g. U-235, U-233, Pu-239.

Fission products: Daughter nuclei resulting either from the fission of heavy elements such as uranium, or the radioactive decay of those primary daughters. Usually highly radioactive.

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

Fissionable (of an isotope): Capable of undergoing fission: If fissile, by slow neutrons; if fertile, by fast neutrons.

FSU: Former Soviet Republics

Fossil fuel: A fuel based on carbon presumed to be originally from living matter, e.g. coal, oil, gas. Burned with oxygen to yield energy.

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

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

G

Gamma rays: High energy electro-magnetic radiation from the atomic nucleus, virtually identical to X-rays.

Generation III: Third generation advanced nuclear reactor

Generation IV: Fourth generation advanced nuclear reactor

Genetic mutation: Sudden change in the chromosomal DNA of an individual gene. It may produce inherited changes in descendants. Mutation in some organisms can be made more frequent by irradiation (though this has never been demonstrated in humans).

Giga: One billion units (e.g. gigawatt 109 watts or million kW).

Graphite: Crystalline carbon used in very pure form as a moderator, principally in gas-cooled reactors, but also in Soviet-designed RBMK reactors.

Greenhouse gases: Radioactive gases in the earth's atmosphere which absorb long-wave heat radiation from the earth's surface and re-radiate it, thereby warming the earth. Carbon dioxide and water vapour are the main ones.

GWd / MTIHM: Gigawatt days of thermal output per metric tonne initial heavy metal.

GWe: Gigawatt capacity of electrical output.

GWh: Gigawatt hours, refers largely to the electrical output (GWe) over a period of time in hours.

H

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

Heavy water reactor (HWR): A reactor which uses heavy water as its moderator, e.g. Canadian CANDU (pressurised HWR or PHWR).

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

HEU: Highly enriched uranium often obtained from military applications

HEU-II: The Second phase of the HEU agreement between Russia and the US. Due to start in 2014.

Highly (or High)-enriched uranium (HEU): Uranium enriched to at least 20% U-235. (That in weapons is about 90% U-235.)

I

IAEA: International Atomic Energy Agency

IEA: International Energy Agency. Publishes the World Energy Outlook, last available publication was September 2004.

In situ leaching (ISL): The recovery by chemical leaching of minerals from porous orebodies without physical excavation. Also known as solution mining.

K

Kazakhatomprom: Kazakh national atomic company

Known Conventional Resources (KCR): combined RAR and EAR(I)

L

LEU: low-enriched uranium, uranium suitable for use in civil reactors.

Light Water Reactors (LWR): a common nuclear reactor cooled and usually moderated by ordinary water. LWRs account for 88% of the global total. Moreover, they account for 72% of those currently under construction (figures from WNA website).

Light water: Ordinary water (H20) as distinct from heavy water.

Low-enriched uranium: Uranium enriched to less than 20% U-235. (That in power reactors is usually 3.5 - 5.0% U-235.)

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

M

Massachusetts Institute of Technology (MIT): authors of the major multi-disciplinary report - The Future of Nuclear Power in 2003.

Megawatt (MW): A unit of power, = 106 watts. MWe refers to electric output from a generator, MWt to thermal output from a reactor or heat source (e.g. the gross heat output of a reactor itself, typically three times the MWe figure).

Metal fuels: Natural uranium metal as used in a gas-cooled reactor.

Milling: Process by which minerals are extracted from ore, usually at the mine site.

Moderator: A material such as light or heavy water or graphite used in a reactor to slow down fast neutrons by collision with lighter nuclei so as to expedite further fission.

MOX: Mixed Oxide fuel. Spent fuel discharged from light-water reactors contains appreciable quantities of fissile (U-235, Pu-239), fertile (U-238), and other radioactive materials. These fissile and fertile materials can be chemically separated and recovered from the spent fuel. The plutonium, as an oxide, is mixed with depleted uranium left over from an enrichment plant to form fresh mixed oxide fuel.

N

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

Neutron: An uncharged elementary particle found in the nucleus of every atom except hydrogen. Solitary mobile neutrons travelling at various speeds originate from fission reactions. Slow (thermal) neutrons can in turn readily cause fission in nuclei of "fissile" isotopes, e.g. U-235, Pu-239, U-233; and fast neutrons can cause fission in nuclei of "fertile" isotopes such as U-238, Pu-239. Sometimes atomic nuclei simply capture neutrons.

Nuclear Energy Agency (NEA): OECD publishers of the *Red Book*.

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

Nuclear Regulatory Commission (NRC): US NRC is an independent agency established by the Energy Reorganization Act of 1974 to regulate civilian use of nuclear materials**.**

Nuclear Suppliers Group (NSG): 44 members of the NSG include: Canada, Australia, Kazakhstan, the US, the UK, China, Russia, South Korea and Japan. It provides strict guidelines related to uranium trade and other nuclear issues.

O

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

P

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

Pressurised water reactor (PWR): The most common type of light water reactor (LWR), it uses water at very high pressure in a primary circuit and steam is formed in a secondary circuit.

R

Radiation: The emission and propagation of energy by means of electromagnetic waves or particles. (cf ionising radiation).

Radioactivity: The spontaneous decay of an unstable atomic nucleus, giving rise to the emission of radiation.

Radionuclide: A radioactive isotope of an element.

Radiotoxicity: The adverse health effect of a radionuclide due to its radioactivity.

Radium: A radioactive decay product of uranium often found in uranium ore. It has several radioactive isotopes. Radium-226 decays to radon-222.

Radon (Rn): A heavy radioactive gas given off by rocks containing radium (or thorium). Rn-222 is the main isotope.

Radon daughters: Short-lived decay products of radon-222 (Po-218, Pb-214, Bi-214, Po-214).

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

Reasonably Assured Resources (RAR): known resources with detailed estimates, and are considered to have a high assurance of existence.

Red Book: The most authoritative source for uranium information, published jointly by the OECD and the IAEA. Published every two years, last published 2005.

Repository: A permanent disposal place for radioactive wastes.

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

S

Spent fuel: Fuel assemblies removed from a reactor after several years use.

Stable: Incapable of spontaneous radioactive decay.

T

Tailings: Ground rock remaining after particular ore minerals (e.g. uranium oxides) are extracted.

Tails: Depleted uranium (cf. enriched uranium), with about 0.3% U-235; often refers to the U-238 stream that is removed during enrichment (containing 0.25-0.35% U-235).

Thermal efficiency - ratio of the electrical output and the thermal input as expressed as a percentage, typically 33-35%. This is not to be confused with burn-up.

Thermal reactor: a reactor in which the fission chain reaction is sustained primarily by slow neutrons, and hence requiring a moderator (as distinct from Fast Neutron Reactor).

Transmutation: Changing atoms of one element into those of another by neutron bombardment, causing neutron capture.

Transuranic element: A very heavy element formed artificially by neutron capture and possibly subsequent beta decay(s). Has a higher atomic number than uranium (92). All are radioactive. Neptunium, plutonium, americium and curium are the best-known.

Terawatt hours (TWh): is equivalent to 1 thousand GWh, 1 million MWh, or 1 billion kWh.

U

U-235: Typical term for Uranium 235 isotope.

U-238: Typical term for Uranium 238 isotope.

U_3O_8: Uranium oxide, also known as yellowcake.

UF_6: Uranium Hexafluoride. The gaseous product from converting U3O8 prior to enrichment.

UOX: Uranium Oxide fuel. The fuel that powers the vast majority of the world's reactors

Uranium (U): A mildly radioactive element with two isotopes which are fissile (U-235 and U-233) and two which are fertile (U-238 and U-234). Uranium is the basic fuel of nuclear energy.

Uranium hexafluoride (UF_6): A compound of uranium which is a gas above 56°C and is thus a suitable form in which to enrich the uranium.

Uranium oxide concentrate (U_3O_8): The mixture of uranium oxides produced after milling uranium ore from a mine. Sometimes called yellowcake, although it is khaki in colour and is usually represented by the empirical formula U_3O_8. Uranium is sold in this form.

Uranium Information Centre (UIC): Australian public information association on the uranium industry established in 1978.

Utilisation (rate): A measure of the proportion of the year a power generator operates for, expressed as either a percentage (%) or hours. One year has 8760.25 hours.

V-Z

Vitrification: The incorporation of high-level wastes into borosilicate glass, to make up about 14% of it by mass. It is designed to immobilise radionuclides in an insoluble matrix ready for disposal.

World Nuclear Association (WNA): http://www.world-nuclear.org/

Yellowcake: Ammonium diuranate, the penultimate uranium compound in U3O8 production, but the form in which mine product was sold until about 1970. See also Uranium oxide concentrate.

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