The Scarcity of Uranium Supplies

Would an increased use of uranium increase the security of supply risk to the global nuclear renaissance by 2030?

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ABSTRACT

The Nuclear Energy Agency and International Atomic Energy Agency anticipate growth in the use of nuclear power, which is expected to double by 2030. This will lead to a significant increase in nuclear fuel demand that will certainly result in substantial requirements for uranium. The availability, affordability, accessibility and acceptability of nuclear fuel are considered in this research as the main indicators for the success of nuclear energy renaissance to ensure energy security. This raises the question of whether uranium as a nuclear fuel would be sufficiently available at affordable prices, easy to access and have no negative impact on the environment by 2030. This thesis focuses on uranium availability and affordability by examining whether or not there will be a risk to the supply of uranium as a nuclear fuel in the future, in particular 2030 and beyond, if a nuclear revival occurs. This study is based on quantitative and qualitative data analysis. Data is collected using secondary data and interviews with geologists, nuclear power consultants and environmentalists.
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**Highly enriched uranium (HEU):** Is uranium having greater than 20 percent U-235. The Russian HEU that is down blended under the HEU Agreement has an enrichment level of about 90 percent 235U (DOE, 2007).

**Light Water Reactors (LWRs):** These are reactors that use water as coolant and moderator. There are two types of LWRs; pressurised water reactors (PWRs) and boiling water reactors (BWRs).

**Low enriched uranium (LEU):** Is uranium that is greater than 0.71 percent U-235 but less than 20 percent. Most nuclear power reactor fuel contains LEU having three to five percent 235U (DOE, 2007).

**Plutonium:** Is a manmade element created in nuclear reactors. If separated from the spent fuel of nuclear power plants by means of reprocessing, plutonium can be made into atomic bombs. In addition, plutonium is also intensely toxic. A speck the size of a pollen grain causes lung cancer (NCI, 2009b).
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CHAPTER 1
INTRODUCTION

1.1. Background

With the need to reduce dependency on fossil fuels, many see nuclear power as a safe, mature technology using a relatively cheap fuel with which to cover the electricity base load, to meet future growing demand and to ensure security of supply. However, the increasing demand for uranium as a fuel will increase costs and also resource dependency in the same way as in the oil and gas markets. At the beginning of May 2009 there were a total of 436 operating nuclear reactors in the world with a total generating capacity of 372 GWe supplying 15 per cent of the world’s electricity, requiring 66 500 tonnes of uranium metal per year (tU/yr) (WNA, 2009d). The Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA) anticipation for the nuclear generating capacity is to increase to about 509 GWe in the low demand case and to about 663 GWe in the high demand case, by 2030. Correspondingly, uranium requirements are projected to rise to meet growing nuclear demand to between 93 775 tU/yr and 121 955 tU/yr (NEA & IAEA, 2008). This raises the question of whether the known global uranium reserves can meet the growing demand of 2030 and beyond.

In the nuclear power debate, security of the uranium supply usually comes late in the list of the main aspects to be considered. However, it should have the highest priority, the same as waste management difficulties, weapons proliferation, nuclear radiation, terrorism, costs of plant decommissioning and construction economics. The primary fuel for nuclear power plants, uranium, is a finite and non-renewable material found in the earth’s crust and oceans. Naturally occurring uranium contains 0.7 per cent of uranium-235 (U-235). The U-235 isotope is required in the fission process for the production of heat used in electricity generation. The natural uranium goes through different production stages – mining, milling, conversion, enrichment – to be used in the nuclear reactor for the fission process.
One of the main motivations for the shift to nuclear power is that the power plants themselves have no effect on climate change since, relatively, they do not emit carbon dioxide (CO₂) emissions during the electricity generation process. However, this overlooks the complete nuclear fuel cycle which is in fact a high CO₂ emissions process: mining uranium requires energy and the extracted uranium is transported hundreds of kilometres from the uranium mines to the enrichment factories. This renders nuclear fuel unsustainable and environmentally unacceptable. In addition, there are issues concerning the accessibility of uranium. The largest world exporters are Canada, Australia and Kazakhstan, countries which are geographically far from Europe and in particular the UK.

Based on the current global nuclear energy map, this research will analyse the potential of uranium-based energy to meet future energy demands. It discusses the issues of availability and affordability of uranium. It will argue that uranium, being a finite resource, will be depleted very rapidly by the increased rates of demand which in turn will raise the price of uranium. This may lead to the unavailability and the unaffordability of nuclear fuel.

As fuel is the main aspect in any new power plant feasibility study, it may be that nuclear power is not the solution for achieving an energy security policy. It could delay a sustainable development strategy and fail to combat climate change. Moreover, investment in nuclear power, rather than in sustainable technology, may be a waste of both time and money.

1.2. Aims and objectives

The main aim of this thesis is to examine whether or not the projected increase in use of uranium will lead to security of supply risk; to understand the degree to which the uranium ores grades will become scarce; and to consider the implications for the economics of nuclear power.
The objective of this research is to demonstrate whether or not the global reserves of uranium are able to meet the two main elements of the security of supply: availability and affordability by:

- Examining the degree to which uranium will become scarce on projected increase in demand for the new nuclear ‘renaissance’ – availability
- Studying the history and current state of the uranium market in order to forecast future expectations of uranium prices – affordability

1.2.1 Research questions

1. Can the uranium reserves meet the growing demand for nuclear fuel for use in electricity generation?
2. What are the uranium cost implications for the economics of nuclear power if high-grade uranium is depleted?
3. Do the current global energy policies favouring nuclear power take into consideration the future security of the uranium supply?

1.3. Structure of the study

In this chapter, the background of the research problem is introduced and the research aims and objectives are outlined. Chapter two presents a review of the literature. The research methods that have been used to conduct this research are discussed in chapter three. Chapter four is divided into five sections: 4.1 explains the principles of nuclear power generation and the nuclear fuel cycle; 4.2 examines the current status and the future projections for nuclear power; 4.3 analyses uranium exploration; production; and supply and whether the anticipated increase in uranium demand by 2030 can be met; 4.4 presents the uranium trade and the history of uranium and 4.5 examines the cost of nuclear fuel and its impact on the economics of nuclear power. Chapter five discusses the outcome and results of this research before the conclusion and recommendations are drawn in chapter six.
CHAPTER 2
LITERATURE REVIEW

This chapter will present the literature review on the uranium availability for assessing future nuclear power validity issue.

2.1 Background

The history of investigation and research of the uranium resources adequacy and the production capability to supply nuclear reactors began in the mid 1960s, when nuclear power programmes were set up for use in civil purposes and mainly for electricity generation. Since then, the uranium industry has suffered severe fluctuations in production due to diverse predictions of future uranium requirements, which, in turn, has affected the uranium prices and availability throughout its history.

The status of the uranium industry in the 1970s was characterised by an extreme over-supply. This was as a consequence of the optimism about future expansion in the nuclear electricity generation capacity that started in the late 1960s, along with the expectation of a consequent increase in uranium prices. This in turn, incentivised uranium producers to produce more uranium to meet this anticipated growing demand, despite the depressed uranium prices at this time. Surprisingly, the late 1960s, uranium demand forecast was over-estimated and the actual uranium requirement was under what was anticipated (Radetzki, 1981).

Despite this over-supply that should have led to low uranium prices, conversely, uranium prices boomed due to the highest price in the mid 1970s. This price explosion was due to various factors, in particular the 1973 oil crisis, which, as a consequence, resulted in new energy policies for Western Europe in general. Along with political decisions and interventions by governments of energy-supplying countries inferred the uranium market, which, in turn, affected uranium prices significantly (Radetzki, 1981).
This led to the judgments of longer-run adequacy of low-cost uranium resources to meet future nuclear power growth becoming more ambiguous and elusive.

Since the late 1980s, when the demand exceeded production and secondary sources began to compensate the difference in demand, the uranium availability debate has changed considerably.

### 2.2 Uranium: Geopolitical availability and storage facility

Uranium resources are distributed widely around the world and particularly in OECD countries. This seems to be a significant incentive for ensuring security of uranium supply for OECD countries. This is because about 40% of known uranium resources are found in OECD countries, such as Canada, Australia and the United States, which are more stable politically and economically than countries supplying oil and gas, which are located mainly in the Middle East and the Russian Federation and controlling some 70% of world crude oil and natural gas reserves (Price, 1984; Price & Blaise, 2002). In addition, Price and Blaise (2002) argue that OECD countries are self-sufficient in the ‘front-end’ fuel cycle facilities, such as conversion, enrichment and fuel fabrication processes, which convert the mined uranium raw material into nuclear fuel suitable for use in nuclear reactors, which ensures security of the supply of nuclear fuel.

Furthermore, uranium is unique, since it can be stored easily and cheaply for several years. However, oil pipeline storage is limited to just three months. Uranium availability is, therefore, somewhat guaranteed for several decades, at affordable prices to supply pressurised water and other types of thermal reactors, to generate electricity at costs that will be cheaper with those for generation from fossil fuels. Thus, uranium availability is unlikely to be a constraint for implementation of nuclear power over the next four decades (Price, 1984).
2.3 Uranium: Economic availability

The abundance of uranium element in the Earth’s crust, with extensive diversity of uranium deposits occurring enormously in rocks of wide range of geological age and distribution, which will certainly yield to more production and exploration, is seen to be a durable foundation for ensuring secure uranium supplies, and impeding suspicions in addressing future uranium scarcity (Price, 1984; MacDonald, 2003). In addition, the uranium industry is described as being a youthful industry; its history began in the late 1970s with the first and only cycle of exploration, discovery, and production since then. Given that the unconformity deposits - which are the most significant type of deposits - were not included in this cycle, though, this cycle was capable of meeting the needs of more than half a century of nuclear energy demand (MacDonald, 2003).

MacDonald (2003) argues that uranium supply is ‘economically sustainable’, like any other metal commodity, and that uranium can certainly be replenished in a normally functioning uranium market. This may happen through incentivised high spot prices and renewed prospects for the nuclear generation growth, along with technological change, to enhance new exploration, new discoveries, and production cycle, which, in turn, will generate new uranium resources to replace depleted ones. Bodansky (2004), on the other hand, disputed the economic view, arguing that, despite the abundance of conventional uranium for the next several decades, the possibility of uranium shortage may exist over the 21st century as a whole if the nuclear industry expands intensely and vast amounts of the lower grade resources cannot be extracted effectively.

Shultis and Faw (2002) analysed the availability of uranium in relation to the uranium resources types, and, the extent to which the uranium exploitation from these resources are economically viable. During the next two-to-three decades, uranium will be produced from reasonably assured reserves for price type category no more $130/KgU, where these reserves are estimated to be 4million tonnes in total. For the same cost production category, the speculative resources will be developed within the next thirty decades. Hence, the speculative resources estimate is based on geological similarities of
similar deposits and other indirect evidence, which indicates that additional uranium resources can be discovered (Shultis & Faw, 2002).

2.4 Uranium: Energetic availability

The availability of uranium is determined by the net energy generated, in which this net energy is the difference between the amount of energy generated from 1 kg of natural uranium and the amount of energy required to recover it from the ore (Storm Van Leeuwen, 2007a). The lower the grade of the ore, the more energy is needed to mine and mill it. In fact, most of this energy is derived from the burning of fossil fuels (Fleming, 2007). The previously known high-grade uranium deposits are depleting and, from a geological point of view, the opportunities of discovering new, large, rich ores are relatively low. Thus, the remaining low-grade ores will utilize more energy for extraction, than that will be generated (Fleming, 2007; Storm Van Leeuwen, 2007a).

Based on two proposed scenarios in the Secure Energy report, Storm Van Leeuwen (2007a) argues that, at a certain point in time, either 2050 or 2070, depending on the rate of uranium consumption and the global nuclear power generation capacity, the nuclear system will suffer from an energy cliff, due to a substantial decline of the net energy produced. Simultaneously, Fleming (2007) attained the same outlook and stated that the nuclear energy system will suffer from ‘energy bankruptcy’ and that more, rather than less, CO₂ emissions will be emitted. In addition, the decision for more investment into mining will no longer be taken, since there will not be a high payback from the mining process and price of uranium. Shultis and Faw (2002) argue that exploitation of low-grade uranium deposits, in the meantime, is economically unfeasible due to low uranium prices, although significant amounts of uranium may be available. Alternatively, it is the view of the Energy Watch Group (2006) that it is extremely uncertain that undiscovered resources will be included in serious planning for global uranium availability over the next 20-30 years, due to the low probability of their emergence.
2.5 Uranium: Physical availability

In general, the measure of the remaining resources can be considered a crucial indicator for security of supply (Kruyt et al., 2009). This is not the case with uranium. The current estimates of total global uranium resources are criticized for being uncertain and conservative. Moreover, there is no pragmatic knowledge of how long uranium resources will last, and that a meaningful total of global uranium resources cannot be established (Bodansky, 2004; Mobbs, 2005; Macfarlane & Miller, 2007). This is due to the limited exploration of undiscovered resources that is affected by the relatively low uranium prices. Inadequate methodologies used in the uranium resources estimation, since “they are entirely based on the economic costs of production, not the net energy value of the resource once the costs of extraction and use are taken into account” (Mobbs, 2005: p.3). In addition, a number of countries conceal their uncertain uranium resources or those in high-cost categories (Bodansky, 2004; Mobbs, 2005; Macfarlane & Miller, 2007).

Taking this into account, Bodansky (2004) provides a conservative estimate of 20 million tonnes as a total for uranium resources, which would be sufficient for 80 years to meet four times the world nuclear electricity generation from 2004 (300 GWe/yr), at the current use of light water reactors (LWRs) which consumes 200 tonnes of uranium per one gigawatt per year. Bodansky (2004) predicts that, in the case of huge nuclear expansion during the next 50-100 years by using LWRs with the same uranium consumption rate, uranium supplies may become a constraint.

Known uranium resources would last for 42 years at a uranium consumption rate of 67,000tu/yr (Mobbs, 2005). Furthermore, Mobbs (2005) adopted the involvement of secondary sources, such as military inventories, in addition to the known and estimated resources in the interpretation of uranium resources lifetime. These may continue for 72 years at the current share of nuclear power in the world’s energy supply. However, if nuclear capacity increased six-fold, then 72 years would be reduced to 12 (Mobbs, 2005).
Radetzki (1981) has argued that it is irrelevant to estimate long-run uranium requirements from the identified reserves or resources, since the latter have been established for mining companies’ planning needs, and dependent on the spread and intensity of past exploration efforts. However, it may be more appropriate to compare future uranium requirements with the assessments of global uranium availability, whether discovered or not, derived from basic geological induction (Radetzki, 1981).

The high degree of reliability and geological knowledge of the reasonably assured resources at production cost categories below 40$/kgU and below 80$/kgU make these two categories the most comparable with crude oil proved reserves (EWG, 2006). Discovered reserves are not sufficient to guarantee uranium supply for more than 30 years on an annual demand rate of 67,000 tU/yr. Moreover, possible resources that contain all estimated discovered resources with extraction costs of up to 130$/kgU will be exhausted within 70 years (EWG, 2006).

The Euratom Supply Agency (ESA) (2007)’s Annual Report presented an overview of the main recent developments affecting global uranium supply and demand balance, as well as security of supply at different stages of the nuclear fuel cycle. ESA stated that:

‘The commonly known indentified resources are sufficient for at least 85 years, if considering 2006 uranium requirements (of about 66 500 tU). If estimates of current usage rates are used, the indentified resources would be sufficient for about 100 years of reactor supply, however the exploitation of the entire conventional resource base (some 16 872 700 tU) would increase this to 300 years.’ (ESA, 2007: p.11)

Accordingly, ESA recommended that more exploration and development would be needed to shift these resources to more definitive categories. However, lack of investment will impede any significant rise in supply. Accordingly, supply constraints can occur at any stage of the nuclear fuel cycle and so, EU utilities need to maintain sufficient uranium stocks and inventories (ESA, 2007).
The NEA and IAEA (2008) stated that, typically, sufficient resources are adequately available to support future nuclear power expansion. In their view:

“The indentified resources are sufficient for over 80 years, if considering 2006 uranium requirements of 66,500 tU. If estimates of current rates of uranium consumption in power reactors are used, then the indentified resources base would be sufficient for about 100 years of reactor supply. Exploitation of the entire conventional resource base - some 16,008,900 tU - would increase this to 300 years.” (NEA & IAEA, 2008: p.88-89)

2.6 Uranium from sea water

The existence of the uranium element in sea water would, potentially, contribute to the uranium security of supply in the long term, after the development of its extraction technology, and countries with access to the sea could, ultimately, have access to vast amounts of uranium (Price & Blaise, 2002; Shultis & Faw, 2002). However, sea water has an average uranium concentration of about 0.003 part per million of uranium (ppmU), in which its extraction will consume more energy than it will produce (Mobbs, 2005; Fleming, 2007).

2.7 Alternative technologies

Price and Blaise (2002)’s interpretation for estimating future uranium resources notes that there are sufficient uranium resources for many centuries to meet the nuclear energy future at current generation rate, or even ten times more, and at various fuel cycle technology options. In addition to this, technological developments, such as the introduction of fast breeder reactors and thorium-based fuel cycles, would extend these periods of availability. However, the utilization of this potential can only be achieved through considerable effort and investment to develop new mining projects and to bring advanced technologies to bear in a timely manner. Fast breeder reactors or Thorium based reactors, though, will not be functioning within the next 25 years, at least. This is due to their long lead time for technology development and market penetration (Mobbs,
2005; EWG, 2006). Moreover, the availability of uranium under any conditions of new
technologies for reserving the uranium resources is a matter of decades, not centuries,
and that will have a significant impact on the future viability of the nuclear industry.

This chapter has presented the literature that has discussed the scarcity of uranium
supplies.
It concluded that uranium availability has four controversial perspectives: geopolitical;
economical; net energy level; and physical. These disciplines have led to distinctive
interpretations of uranium resource estimates.
CHAPTER 3
METHODOLOGY

This chapter will demonstrate the research instruments; and the research methods achieved to address the research problem and question.

3.1 Research approach

Energy security has become a top priority on political agendas in most countries to ensure national security and enhance sustainable development. There is no exact definition of energy security, “as it has different meanings to different people at different moments of time” (Ahajji, 2007, cited in Kruyt et al., 2009: p. 2167). However, the most common definition that has been adopted is that energy security is uninterruptable energy supply at affordable prices that depends on various aspects, such as energy system reliability, and security of supply (Constantini et al., 2007; IEA, 2001 cited in Kim et al., 2009). The anticipated fossil fuels depletion, their high prices and their tensions surrounding geopolitical supply, along with the global warming challenge, have resulted in many countries considering nuclear power as an alternative energy source to ensure energy security and combat climate change (Kim et al., 2009; Kruyt et al., 2009). This has raised the question as to whether nuclear power will ensure the energy security needed, given that uranium, as a nuclear fuel, is a finite resource, almost typically the same as oil and gas, and as a basic general rule, finite resources will run out with increased use.

Combs (2004) argues that, if nuclear power is to be a significant part of the future energy solution, then the issue of fuel availability needs to be addressed. Correspondingly, Mobbs (2005) suggests that the limitation on the availability of uranium, and the current state of reactor technology, must be adopted in order to decide how valid nuclear power can be an option. This implies that the study of uranium availability is crucial in identifying if there might be a risk of scarce uranium supplies
in the future, if the anticipated uranium demand forecast by the NEA & IAEA increases to 93 775 tU in a low-demand case and 121 955 tU in high-demand case by 2030.

This research hypothesis is to be based on the definition of Security of Supply (SOS) proposed by the Asia Pacific Energy Research Centre (APERC, 2007 cited in Kruyt et al., 2009). According to that definition, SOS is classified into four main elements:

- Availability – geological existence
- Accessibility – geopolitical elements
- Affordability – economical elements
- Acceptability – environmental and societal elements

The main concept of this research is that the successful implementation of any energy security policy is through attaining these four main elements for any given supply. This research will focus on two elements: availability and affordability of uranium.

3.2 Research design

First, the research began by developing understanding of the basic technical principles of nuclear power generation and how much nuclear fuel is needed to fuel a nuclear power station for one year. The content of nuclear fuel, the relationship between the fuel that is installed into nuclear reactors and the natural uranium were analysed and the front end of the nuclear fuel cycle was studied.

Second, mineral terminologies were approached to distinguish between deposits, resources and reserves to be able to approach uranium resources’ geographical distribution and their level of existence in countable data. The 2008 NEA & IAEA’s ‘Red Book’ was used to determine location and size of global uranium reserves, demand, production, and supply. In addition, this research has used its projected nuclear power generation capacity and uranium requirements by the year 2030 because it is the only source that this research has examined that presents the projected nuclear capacity with projected amount of uranium needed for this capacity by 2030. ESA (2007) used
the 2006 NEA & IAEA future nuclear power capacity and uranium demand scenarios. The ‘Red Book’ is referenced in most of the literature (e.g. Prise & Blaise, 2002; Bodansky, 2004; EWG, 2006).

Since the mid-1960s, the ‘Red Book’ is jointly published by the OECD Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA), and is updated every two years. It is the most authoritative publication assessing global uranium resource estimates based on categories of geological certainty and production cost, and mine production capability with anticipated uranium requirements arising from projections of installed nuclear capacity. Moreover, the ‘Red Book’ presents the current data on uranium resources, exploration, production, and uranium stocks. Data presented in the publication is based on questionnaires sent by the NEA to the OECD member countries and by the IAEA for those states that are not OECD member countries (NEA & IAEA, 2008).

The ‘Red Book’ has been criticized for presenting misleading and flawed estimates of uranium resources. This is because it is based on a small number of reported countries, in which some present partial reports (for instance, Australia did not report resources in speculated resources above $130/kgU); exclusion of resources in the $130/kgU to $260/kgU category; lack of comprehensive studies of resources; neglected uranium mining and milling losses in recoverable uranium resources, which should have been taken into consideration since it represents around 10% of recoverable uranium (Bodansky, 2004; Busby, 2008). Storm Van Leeuwen (2008b) has disputed the nuclear power and uranium requirements outlook, stating that it may be considered highly speculative, and ignores the thermodynamic aspects of the nuclear system (Storm Van Leeuwen, 2008b). However, these uncertainties were taken into consideration in the data analysis and checked in other sources, such as the mines production capacities; these were double checked from the mining companies websites.

Third, study of the uranium market history and the implications of external factors that affected the uranium production and prices were examined. This section was mainly approached from the ‘Uranium: A strategic Source of Energy’ book, edited by Radetzki,
1981. This book has analysed the factors that was primarily responsible for the mid 1970s uranium prices volatility and included comprehensive analysis of the international uranium market development from its inception until 1980. After this period, Macdonald (2003) and Combs (2004) were the sources.

After these three stages, a good understanding of the research problem has been attained and basic guidelines in assessing it; in which the strengths and weakness were almost determined. Then, followed by the fourth stage which is conducting interviews (more details are discussed later in this chapter) and writing transcripts.

Last, qualitative and quantitative secondary data and evidences; along with interviews outcome were analysed and the research discussion and conclusion were drawn.

### 3.3 Data collection

The research used both qualitative and quantitative data, based on interviews and secondary data. For the literature review, secondary data were applied for gaining deep understanding and information of the research topic. However, there were constraints in finding secondary data:

#### 3.3.1 Research gap

There is limited literature for the topic under study. Through the various sources (academic journals, University Library, and internet) this research has inspected, research on the availability of uranium is rare. There was intensive research during late 1970s until the mid 1980s, after which, there was a gap in research for almost two decades. A revival in research started from about 2003, most probably restarted with the renewed interest of nuclear power by several countries.
3.3.2 Confidential data

It is very important to examine the impact uranium availability on future nuclear fuel supplies and the scarcity of uranium resources. Statistics and size of uranium secondary sources are not available or published; data are kept confidential for political concerns. However, it is very important to examine its impact on future nuclear fuel supplies and the scarcity of uranium resources.

Secondary data were collected from library references and valid electronic resources such as the International Atomic Energy Agency (IAEA); World Nuclear Association (WNA), formerly was the Uranium Institute; and the Nuclear Energy Agency (NEA). Evidence from academic journals, academic books, independent researchers, media coverage, NGOs, and government documents (consultations, papers, websites), which were available to the public and to researchers, were accessed and collected.

3.3.3 Interviews

Interviews are chosen as a method of data collection in this research due to the lack of data and lack of previous research on the research topic. Interviews will help to gain insightful understanding of, and learning from, different experiences in the uranium mining industry, uranium market and how energy policy-makers address the issue of security of uranium supplies in the debate over decision-making of pursuing nuclear power. Denscombe (2007) argues that the interview’s potential as a research methodology is exploited better when they are applied to the exploration of more complicated and subtle phenomena. Interviews are more appropriate than questionnaires if the researcher needs to acquire data related to feelings, emotions, opinions, experiences, sensitive issues and privileged information (Denscombe, 2007).

Radetzki (1981) conducted interviews in researching uranium market development. Storm Van Leeuwen, in an interview, mentioned that his continuous updating and refinement of the nuclear energy system assessment is based on collaboration with many scientists and universities all over the world. Most literature has not mentioned methodology.
From the early stages of the research, 12 interviewees were contacted to take part in this research. They were drawn from various backgrounds: geologists, nuclear power consultants, environmentalists, nuclear power economists and academics; nuclear power policy-makers, energy utilities, and nuclear and mining industry actors. This is to assess all the different views related to this multi-disciplinary research problem. Early notice was essential, since most interviews were conducted in late July 2009, and this time of the year is when many people take annual leave.

Respondents from British Energy, which is part of EDF Energy, were not able to participate in this research without specifying any reason, but they advised the researcher to contact the Nuclear Industry Association (NIA), and forwarded some of their contacts details. Accordingly, NIA contacts were contacted twice, taking British Energy as the reference, although there was no reply. Simultaneously, nuclear policy advisors in the Department of Energy and Climate Change (DECC) were unable to participate in this research due to their busy working agendas; there was no reply from other nuclear strategy actors in the DECC. These negative responses resulted in less effective examination and answer to the third research question regarding the energy policy views in approaching the uranium security of supplies issue.

Moreover, no replies were received to enquiries sent through emails to contacts in Ux Consulting Company, which publishes uranium spot prices, and general enquiries to Cameco the Canadian uranium mining company regarding the uranium market and the uranium mining industry yielded no response.

3.3.4 Participants

Five out of 12 responded and agreed to participate in this research through face-to-face interviews. Two geologists -Dr Frances Wall and Dr Richard Pasco - who are mining academics based in Cornwall, have been to the Rossing mine in Namibia and have experience within the uranium mining industry in Namibia, were involved in the second stage of the research in early July. The interviews concentrated on what factors affect the existence of resources; how uranium mining industry works; what incentives,
barriers, and factors affect the resources explorations and discoveries processes; rate of production; and methods of extraction.

In late July, two interviews were conducted with Professor Stephan Thomas, who is an academic and nuclear power economist, and Dr David Fleming, an environmentalist. Both were in London. These interviews focused on the uranium cost implications on economics of nuclear power; role of secondary sources, in particular the use of mixed oxide fuel (MOX) and role nuclear energy alternatives; the uranium industry production capabilities; and the energy policies views in assessing the uranium security of supplies.

The interviews were recorded digitally and lasted for around 90 minutes. With each participant, except Dr Pasco, notes were taken. Interviews were semi structured. Questions were prepared on subjects needing to be answered and addressed, although there was flexibility in expressing ideas and views. This method provided relevant perspectives and concerns that not may have been provided if any other type of interviews, such as structured interviews and unstructured interviews, had been applied. Denscombe (2007) suggests that the semi-structured interview develops a relaxed environment for the interviewee to come with ideas and provide their experiences and views more widely on the aspects raised by the researcher.

The time and financial restrictions, along with long visa entry procedures to other countries, limited travel to other countries outside the UK for conducting face-to-face interviews. The interview with Jan Willem Storm Van Leeuwen was conducted through email because the participant is based in the Netherlands. This interviewee is an independent nuclear power consultant at Ceedata consultancy; and has a significant record of publications in the assessment of nuclear power. In addition, he has a unique contribution in addressing the availability of uranium resources, and has been acknowledged by David Fleming in his book, *The Lean Guide to Nuclear Energy*.

### 3.4 Data analysis

The data analysis is the most essential and sensitive part of the research. It transforms gathered data to a final, useful statement. It involves the exploration of hidden evidence
and data that imply the reality of the research problem, and yields to the research outcome and recommendations (Denscombe, 2007). This research attempted to reveal the negative impacts and hidden facts regarding the optimistic picture of secure uranium supplies and sustained nuclear fuel provided by some authorized organisations, such as the Nuclear Energy Agency.

There are several approaches for analysing data for social research: content analysis, discourse analysis, qualitative and quantitative analysis. The qualitative and quantitative analyses are the most appropriate approaches for this research.

This chapter has addressed the research approach to, and design of, the issue of the security of uranium supplies. Both interviews and secondary data were chosen for data collection. Confidential data, the research gap, and the negative response of nuclear policy actors were the main research limitations and barriers that have opposed the examination of the policies in addressing the uranium scarcity. This chapter introduced the participants who were involved in this research. Qualitative and quantitative analysis were the criteria for analysing data.
CHAPTER 4
SCARCITY OF URANIUM SUPPLIES

The main purpose is to determine whether or not there will be sufficient primary fuel (uranium) to meet the growing global uranium demand needed by the nuclear renaissance by 2030. Thus, it is significant to understand the current status of nuclear power generation and the primary uranium production, and their capabilities in development and expansion to meet any future nuclear energy policies targets, in particular by 2030. This chapter will cover the current and under construction nuclear reactors and uranium mines, worldwide. It will present the basic principles of understanding the nuclear energy generation and the mining terminologies in order to explore the nuclear fuel cycle, the uranium resources and production figures, so as to aid relevant interpretation and analysis. Furthermore, it will present the relation between the uranium supply and demand throughout the history of uranium market and its impact on the uranium prices. In addition, the cost of raw uranium implication on economics of nuclear power will be addressed.

4.1 Principles of nuclear power

A nuclear power station for generating electricity is similar to a coal, natural gas, and oil power stations in most respects. Intense heat derived from the primary fuel (coal, gas, oil or uranium) is used to convert water into steam, which drives turbine-generator system to generate electricity. Given this general definition, heat is produced in coal, gas and oil power plants through burning of fossil fuels, which is the main contributor to carbon dioxide emissions, which causes global warming. However, in nuclear reactors, heat is generated through the nuclear fission using uranium as the fissile material, where no greenhouse gases are emitted, which is considered to be the key incentive in combating climate change (Shepherd, 2007).
4.1.1 Nuclear fission

Uranium is used as a fuel because of it being the heaviest atom of all the naturally occurring elements and the most energy intensive. It has three isotopes - designated U234, U235 and U238. U235 is the most compatible isotope for the nuclear fission, since it has the highest energy production potential, under certain physical conditions when its nucleus absorbs an extra neutron. It splits into two fragments of roughly equal mass, generating a vast amount of energy in the form of heat and releasing two or three more neutrons plus some gamma radiation. When the released neutrons are captured by the nuclei of other U-235 atoms to split, releasing further neutrons, a fission 'chain reaction' occurs. When this process happens several times, a very large amount of heat is produced from a relatively small amount of uranium (Shepherd, 2007; WNA, n.d). One kilogram of uranium produces heat equivalent to that generated from 20 tonnes of coal (WNA, n.d). To supply enough enriched fuel for a standard 1000 MWe reactor for one full-power year, about 200 tonnes of natural uranium has to be processed (Fleming, 2007).

The chain reaction takes place in the core of the nuclear reactor, which is at the heart of the nuclear power station. The core contains the fuel rods, which are surrounded by a moderator material, which is either water, or graphite depending on the type of the reactor to limit the speed of the emitted neutrons for sustained chain reaction. It also contains a coolant to absorb any excess heat from the core; and control rods to absorb any extra produced neutrons not required in the chain reaction. The control rods position in the core controls the chain reaction which in turn controls the amount of heat released. The nuclear power station’s electricity output is controlled, therefore (Shultis & Faw, 2002; British Energy, 2009).

4.1.2 The nuclear fuel cycle

The nuclear fuel cycle, as seen in Figure 4.1, is where the raw uranium undergoes different production stages to be suitable for use in the nuclear reactors as fuel and then this fuel is either disposed or recycled. It is classified into two types: the once-through
mode that discharges spent fuel directly into disposal; and the closed mode that reprocesses the spent fuel through separating the waste products from the unused fissionable material, so that it can be recycled as a fuel. Both nuclear fuel cycles have the front-end process in common, in which the uranium fuel is mined, milled, converted, enriched, and fabricated; the construction of the plant; and the operation and maintenance of the facility (Sovacool, 2008). Table 4.2 shows the global nuclear fuel cycle facilities in operation and under construction.

Figure 4.1 The nuclear fuel cycle

![The nuclear fuel cycle diagram](source: SDC, 2006: P.11)

1. Uranium mining

The natural uranium element is commonly distributed in the Earth’s crust, at different levels of concentration, and in oceans in minute quantities (Table 4.1), with the exception of highly concentrated areas rich enough to comprise ore, found mainly in Canada and Australia (Fleming, 2007; Sovacool, 2008).
Table 4.1: Typical uranium concentration levels

<table>
<thead>
<tr>
<th>Concentration levels</th>
<th>Concentration in Part Per Million (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high grade ore (Canada) – 20%</td>
<td>200,000 ppm U</td>
</tr>
<tr>
<td>High-grade ore – 2% U</td>
<td>20,000 ppm U</td>
</tr>
<tr>
<td>Low – grade ore – 0.1% U</td>
<td>1,000 ppm U</td>
</tr>
<tr>
<td>Very low grade ore (Namibia) – 0.01%</td>
<td>100 ppm U</td>
</tr>
<tr>
<td>Granite</td>
<td>4-5 ppm U</td>
</tr>
<tr>
<td>Sedimentary rock</td>
<td>2 ppm U</td>
</tr>
<tr>
<td>Earth’s continental crust (av)</td>
<td>2.8 ppm U</td>
</tr>
<tr>
<td>Seawater</td>
<td>0.003 ppm U</td>
</tr>
</tbody>
</table>

Source: WNA (2008b)

Uranium is extracted from the mines either by the opencast pits or underground mining techniques, depending on the depth in which the ore body is found, typically up to 250 m deep for the former technique. In some uranium mining, the in situ leaching technique is applied, whereby hundreds of tonnes of sulphuric acid, nitric acid, and ammonia are injected into the strata and then pumped up again after 3-25 years, yielding uranium from the treated rock and depositing vast amounts of radioactive and toxic materials into the environment (Australian Uranium Association, 2004; Fleming, 2007; Sovacool, 2008). The decision as to which mining method is to be used depends on the nature of the ore body; safety; and environmental and economic aspects (Pasco, personal communications).

2. Uranium milling

The mined uranium is sent to the mill, which is usually located near the mines, since the transportation of large volume of rock is very expensive. At the mill, the mined ore undergoes a series of metallurgical processes, where it has to be crushed, screened and washed before leaching in acid or alkali baths to separate uranium from waste rocks. This produces the uranium oxide (U$_3$O$_8$), which is known as the yellowcake that is to be sold afterwards. In the case of ores with a concentration of 0.1%, the milling must grind 1,000 tonnes of rock to extract one tonne of the yellowcake (Fleming, 2007; Sovacool, 2008).
3. Uranium conversion

The uranium must be in the gaseous state for further production processes. The solid state matter U₁₃O₈ is converted to uranium hexafluoride gas (UF₆) - known as hex - through reacting it with fluorine at 56.6°C (Fleming, 2007).

There are around 22 commercial conversion plants operating in nine countries. The largest operate in Canada, France, Russia, and the UK. France has two plants under construction, expected start date in 2012 (IAEA, 2009b).

4. Uranium enrichment

The natural uranium contains about 0.7% of the fissionable uranium isotope U-235, which is required for the fission process in the nuclear reactors. The remainder is mainly U-238 and a tiny amount of U-234. The vast majority of nuclear reactors in operation or under construction require enriched uranium fuel in which the U-235 isotope proportion is raised from 0.7% to around 3.5%, and to around 4-5% for new modern reactors.

The most commonly used enrichment processes are gaseous diffusion method or the centrifuge method, producing around 85% of oxide waste - which contains mainly U-238 isotope - in the form of depleted hex known as enrichment tails/depleted uranium, which must be firmly stored, since it reacts viciously with water including water vapour in the air and explodes. However, some of that waste is converted into depleted uranium metal used in non-energy generation applications. The remaining 15% enriched uranium is sent to the final nuclear fuel production stage (AUA, 2004; Fleming, 2007; Sovacool, 2008).

Globally, there are 13 commercial enrichment plants in operation in China, France, Germany, Netherlands, Japan, Pakistan, Russia, the UK and the US. There are two enrichment plants under construction with expectation to start soon in France with 7500
MTSWU/yr (full-capacity operation by 2016), and in the US with 3000 MTSWU/yr (IAEA, 2009b).

### Table 4.2: Global fuel cycle facilities for commercial use

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of facilities in commercial operation</th>
<th>Number of facilities under construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion</td>
<td>22</td>
<td>2</td>
</tr>
<tr>
<td>Enrichment</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>Uranium fuel fabrication</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Spent fuel reprocessing</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Re-conversion to U₃O₈ (RepU)</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>MOX production</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: (NEA, 2008; IAEA, 2009b)

5. Uranium fabrication

The 15% enriched uranium is converted into ceramic pellets of uranium dioxide (UO₂), packed in zirconium alloy tubes, and bundled together to form fuel rod assemblies for nuclear power reactors (Sovacool, 2008). The 40 operating fuel fabrication facilities are almost always in countries pursuing nuclear power for electricity generation. The US, Russia, Japan, Canada and the UK are countries installing three and more fuel fabrication plants (NEA, 2008; IAEA, 2009b).

6. Reprocessing

The spent fuel from the nuclear reactor may still contain useful fissile materials -about 95% U-238; 1% U-235; 1% Pu (Plutonium); 3% fission products; and 1% transuranic elements - depending on the rate of burn up - which can be separated by chemical and physical processes to produce new nuclear fuel, thus closing the fuel cycle. The reprocessing of spent fuel recovers significant amounts of plutonium that can be fabricated into MOX fuel. In addition, recovered uranium, which is known as Reprocessed Uranium or RepU, can be reused after conversion and enrichment.
Reprocessing may reduce the overall need for natural uranium by around 30% (WNA, 2009), along with high-level wastes.

Supporters of used fuel reprocessing argue that reprocessing reduces the amount of spent fuel needed to be disposed, which, in turn, helps to solve the waste management problem. In addition, it helps to reduce the demand on natural uranium, and conserves the availability of uranium reserves for as long as possible. However, it increases the availability of plutonium, which, in turn, increases the risk of nuclear weapons proliferation, and emits more toxic radiations (NCI, 2009a; WNA, 2009a).

There are only five spent fuel reprocessing plants in operation in France (1700t/yr), the UK (900t/yr) and the Russian Federation (400 t/yr). Japan has an 800t/yr reprocessing plant in the final stages of construction (NEA, 2008; WNA, 2009a).

Historically, reprocessing was first implemented for producing plutonium for use in nuclear weapons formation during World War 2. Subsequently, it went from being for military purposes to commercial purposes in the US, UK, France, Russia, Japan, and India (Walker, 1999; WNA, 2009a).

In the US, commercial reprocessing and plutonium recycling were suspended during the period of presidencies of Gerald Ford and Jimmy Carter. Afterwards, this ban was cancelled, but no subsidies were provided for the building new of commercial reprocessing plants (Walker, 1999; WNA, 2009a).

In 2006, during the Bush administration, the Global Nuclear Energy Partnership (GNEP) was initiated, seeking to promote the expansion of economic and carbon-free commercial nuclear energy, both domestically and internationally, to meet the growing electricity demand, along with the capability of reducing the impacts associated with use of nuclear fuel reprocessing and reducing the proliferation risks. Furthermore, the programme would demonstrate the critical technologies needed to modify the existing system of spent nuclear fuel management, through developing recycling technologies that enhance energy security in a safe and environmentally responsible manner, while simultaneously promoting non-proliferation (NEA, 2008).
Around 20 more countries, such as Australia, Bulgaria, Canada, China, France, Ghana, Hungary, Italy, Japan, Jordan, Kazakhstan, Korea, Lithuania, Poland, Romania, Russia, Senegal, Slovenia, Ukraine, and the UK, are now involved in this partnership (NEA, 2008).

Currently, under President Obama’s administration, the US Department of Energy (DOE) cancelled the Environmental Impact Assessment (EIA) for the GNEP programme, and will no longer provide financial support for the programme, since it will not pursue any commercial reprocessing. In fact, it will support long-term, science-based research and development technologies for nuclear waste management and proliferation process resistance (WNN, 2009a).

4.2 Current and projected status of nuclear power

There is a vast number of nuclear reactors functioning worldwide for various purposes. There are around 280 research reactors in 56 countries operating for scientific research, along with production of medical and industrial isotopes (WNA, 2009b). In addition, power reactors are used to generate electricity for civil and military use. Furthermore, nuclear fuel facilities are also provided for both research and power purposes (ENS, 2009). However, this thesis is concerned with the nuclear power reactors and nuclear fuel facilities that are used for generating electricity for commercial use.

4.2.1 Current and planned nuclear power capacity

In 31 countries, as of May 2009, there were 436 nuclear power reactors in operation, with a total generated capacity of approximately 372 GWe, and concentrated mainly in the OECD countries. This capacity provides around 15% of the world electricity (WNA, 2009). The major nuclear power-generating countries are the US, France, Japan and Russia, accounting for around 62% of the world’s nuclear generation. As there are over 40 new nuclear power reactors under construction in 14 countries with an anticipated total installation capacity of about 39 GWe (WNA, 2009). Table 4.3 shows a list of countries with current number of reactors in operation and under construction.
Globally, around 112 nuclear power reactors, with a total generating capacity of approximately 130 GWe are planned, along with almost 272 reactors proposed to be installed by 2030. Nuclear power is currently being considered by countries that have never experienced it before in their electricity generation mix. They include Turkey, Poland, Italy, Thailand, Kazakhstan, Israel, Vietnam, the United Arab Emirates (UAE) and Egypt (WNA, 2009).

4.2.2 Types of reactors

The Light Water Reactor (LWR) is the most dominant type of reactors technology (approximately 80%) installed worldwide. Most reactors currently under construction are LWRs with most Pressurized Water Reactors (PWR). This type of reactor uses ordinary water (H$_2$O) as a moderator and as the coolant and heat transfer fluid. It requires enriched uranium as a fuel.

The Pressurized Heavy Water Reactors (PHWR) is used typically in Canada, commonly known as CANDU, and in India. High-pressure heavy water (D$_2$O) is used as moderator and coolant. Conversely, this type of reactor consumes natural uranium as a fuel, without the need for enrichment, as is needed in other types of reactors.

The vast majority of reactors installed in the UK are Gas–Cooled Reactors (GCR), which are available in the UK only, although Sizewell B is a PWR. Graphite is used as moderator, and the heat is transferred to the external heat exchangers using high-pressure carbon dioxide (CO$_2$). It requires 2.3% of enriched uranium. At present, there are no GCRs under construction. The remaining operating type of reactors is Light Water Cooled Graphite Moderated Reactors, along with two fast breeder reactors in France and Russia, while two Fast Breeder Reactors (FBRs) are under construction in Russia and India (Shepherd, 2007; NEA, 2008; IAEA, 2009a).
Table 4.3: Global nuclear generating capacity in operation and under construction

<table>
<thead>
<tr>
<th>Country</th>
<th>In operation</th>
<th>Under construction</th>
<th>Expected start date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of reactors</td>
<td>Generating Capacity (MW)</td>
<td>Generating Capacity (MW)</td>
</tr>
<tr>
<td>Argentina</td>
<td>2</td>
<td>935</td>
<td>692</td>
</tr>
<tr>
<td>Armenia</td>
<td>1</td>
<td>376</td>
<td>-</td>
</tr>
<tr>
<td>Belgium</td>
<td>7</td>
<td>5728</td>
<td>-</td>
</tr>
<tr>
<td>Brazil</td>
<td>2</td>
<td>1901</td>
<td>-</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>2</td>
<td>1906</td>
<td>-</td>
</tr>
<tr>
<td>Canada</td>
<td>18</td>
<td>12 652</td>
<td>1500</td>
</tr>
<tr>
<td>China</td>
<td>11</td>
<td>8 587</td>
<td>12100</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>6</td>
<td>3472</td>
<td>-</td>
</tr>
<tr>
<td>Finland</td>
<td>4</td>
<td>2696</td>
<td>1600</td>
</tr>
<tr>
<td>France</td>
<td>59</td>
<td>63 473</td>
<td>1630</td>
</tr>
<tr>
<td>Germany</td>
<td>17</td>
<td>20 339</td>
<td>-</td>
</tr>
<tr>
<td>Hungary</td>
<td>4</td>
<td>1826</td>
<td>-</td>
</tr>
<tr>
<td>India</td>
<td>17</td>
<td>3 779</td>
<td>2976</td>
</tr>
<tr>
<td>Iran</td>
<td>-</td>
<td>-</td>
<td>915</td>
</tr>
<tr>
<td>Japan</td>
<td>53</td>
<td>46 236</td>
<td>2285</td>
</tr>
<tr>
<td>Korea (South)</td>
<td>20</td>
<td>17 716</td>
<td>5350</td>
</tr>
<tr>
<td>Lithuania</td>
<td>1</td>
<td>1185</td>
<td>-</td>
</tr>
<tr>
<td>Mexico</td>
<td>2</td>
<td>1310</td>
<td>-</td>
</tr>
<tr>
<td>Netherlands</td>
<td>1</td>
<td>485</td>
<td>-</td>
</tr>
<tr>
<td>Pakistan</td>
<td>2</td>
<td>400</td>
<td>300</td>
</tr>
<tr>
<td>Romania</td>
<td>2</td>
<td>1310</td>
<td>-</td>
</tr>
<tr>
<td>Russia</td>
<td>31</td>
<td>21 743</td>
<td>5980</td>
</tr>
<tr>
<td>Slovakia</td>
<td>4</td>
<td>1688</td>
<td>840</td>
</tr>
<tr>
<td>Slovenia</td>
<td>1</td>
<td>696</td>
<td>-</td>
</tr>
<tr>
<td>South Africa</td>
<td>2</td>
<td>1842</td>
<td>-</td>
</tr>
<tr>
<td>Spain</td>
<td>8</td>
<td>7448</td>
<td>-</td>
</tr>
<tr>
<td>Sweden</td>
<td>10</td>
<td>9016</td>
<td>-</td>
</tr>
<tr>
<td>Switzerland</td>
<td>5</td>
<td>3237</td>
<td>-</td>
</tr>
<tr>
<td>Taiwan</td>
<td>6</td>
<td>4916</td>
<td>2600</td>
</tr>
<tr>
<td>Ukraine</td>
<td>15</td>
<td>13 168</td>
<td>-</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>19</td>
<td>11 035</td>
<td>-</td>
</tr>
<tr>
<td>USA</td>
<td>104</td>
<td>101 119</td>
<td>1180</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>436</strong></td>
<td><strong>372 220</strong></td>
<td><strong>39 948</strong></td>
</tr>
</tbody>
</table>

Source: (WNA, 2009; IAEA, 2009a)
4.2.3 Share of nuclear power

Nuclear power is a substantial source of electricity generation in most of the countries pursuing it (Figure 4.2). Although the US, Japan, and Russia have the world’s largest nuclear power-generating capacities, it represents only around 20%, 24% and 17% of their total annual electricity generation respectively. France is the largest country in the world that depends on nuclear energy, with around 76% of its total annual electricity production coming from nuclear power. In addition, almost 16 different countries rely on nuclear power to generate more than one quarter of their electricity such as Lithuania, Belgium, Finland and Germany (WNA, 2009d).

4.2.4 Nuclear power policies

In recent years, there have been significant modifications in nuclear energy policies worldwide. In Europe, Belgium Germany, Spain, and Sweden have adopted nuclear phase out strategies by 2021-2025 and prohibited new nuclear power reactors build, due to various aspects such as public disagreement, adoption of renewable energy and demand reduction, and difficulties in nuclear waste management. However, there are still political disagreements on nuclear phasing out, particularly in Germany, where there are anticipations that this decision will be reformed after the 2009 general elections (NEA, 2008; Nicola, 2008).

Conversely, France and Finland are proceeding with their nuclear energy policies, and each has proposed the creation of a reactor. France is planning to build a 1630 MWe reactor. Simultaneously, the UK reconsidered the built of new nuclear power plants in 2008.

The vast number of reactors now being built are mainly in Asia. China, in particular, is moving forward with nuclear power to meet its growing electricity demand to enhance its fast-growing economic development, with plans to build around 30 new nuclear plants by 2020. It is expected that China and Korea will be have the world’s largest installed nuclear power nations in 2020 (NEA, 2008).
Concurrently, Russia has developed a new strategy to expand its nuclear power capacity to compensate its domestic gas demand in electricity generation, in order to maintain its gas export obligations to the EU, since its gas reserves are declining and it is an essential economic driver (Umbach, 2009). It is seeking to double its current nuclear generating capacity to 44 GWe by 2020 (NEA, 2008).

4.2.5 Lifetime extension of existing plants

During most of the 1980s, nuclear power plants operating in countries such as the US, Canada, Finland, Japan, and Russia were intended originally to have a lifetime of up to 40 years. However, several plants have been technically approved on the basis that they are safe and capable of operating for 10 or 20 years more, above the nominal design lifetime. The approval for an extension licence is given, provided that it is mandatory to have a regular and continuous monitoring of operational performance, and comprehensive periodic safety reviews (PSRs), every decade (NEA, 2008). Moreover, a reactor life extension project involves significant design modification, refurbishment and replacement of major components.
In Canada, the life extension of the Gentilly-2 nuclear power plant to until around 2040 involves the replacement of the digital control computers, which monitor and control the reactor and power plant functions (Power Technology, 2009).

The US has extended the operational licences of 53 operating reactors with a range of 40 to 60 years more. The earliest extended licence expiration is by 2029, and the latest is by 2046. A further 17 reactors licence renewals are under review (EIA, 2009).

Finland has extended the lifetime of the Olkiluoto units 1 and 2 to 60 years, whose operations commenced in 1979 and 1982 respectively. In addition, Loviisa’s two reactors were given a 20-year extended operation in 2007, which will allow them to run until 2027 and 2030 respectively (Reuters, 2009).

In 2002, the French 900 MWe reactors, most of which started in the late 1970s or early 1980s, have had their operational licences renewed, to continue operating for a decade. The 20 1300 MWe reactors were given a ten-year extension in 2006 (Reuters, 2009).

In 2000, the Russian Federation announced plans for a 15-year extension for 12 reactors. Eight reactors have been granted these extensions and two have received 5 years extension (WNA, 2009c).

In the UK, two-year extensions were approved for the Oldbury 1 and 2 plants, instead of closing down, at the end of 2008. The 1000 MW Wylfa power plant in Wales has been allowed to continue operating for at least nine moths beyond its expected closure date in March 2010. In addition, a five-year operating extension has been granted to four reactors beyond their scheduled closure in 2014(Reuters, 2009)

Operational licence renewals have been granted in other countries, such as Hungary (2032-2037), the Netherlands, Slovakia (2025), Spain (2019) and Switzerland. In Belgium (2025), Czech Republic, Japan and Slovenia some reactors’ lifetime extensions are being considered and are under review. However, Germany and Sweden are not
considering this issue, due to their nuclear phasing out policies (Reuters, 2009; WNA, 2009c).

4.2.6 Construction stage

It was commonly known that the construction time for building a new power plant was around 100 months. However, this reputation has changed in recent years, with a consistent, average construction time of 62 months currently being attained in Asia. Almost 18 reactors started operation between late 2001 and 2007, three of which were constructed in 48 months or less. A Japanese 800 MWe BWR was connected to the grid in 2002 after a 41-month construction period (NEA, 2008). NEA (2008) suggests that this intensity of execution in construction will reduce the high cost of nuclear power significantly.

4.3 Uranium: Resources, Exploration, and Supply

4.3.1 Mining terminologies

Most mining and exploration companies, stock exchanges and international reporting systems refer to the Australasian Joint Ore Reserve Committee code – known as JORC code - as a common reference and standard for defining and classifying tonnage and grade estimates of mineral deposits as either ore reserves or mineral resources (Moon et al., 2006), and subdividing these as categories depending on the level of geological knowledge and confidence (Figure 4.3).

Mineral deposits are the first outcome of the mineral exploration process. Once the basic knowledge of the existence of the targeted mineral in the area under exploration is discovered, this is set to be the mineral deposit. This is followed by initial evaluation of the deposit to examine its economically viable\(^1\) extraction: whether or not this deposit

\(^1\) The term ‘economical’ means that the extraction of the mineral is viable and justifiable under reasonable investment assumptions
can be mined at a profit. Under reasonable prospects of eventual economic extraction, the concentration or occurrence of the mineral is then known to be the mineral resource.

**Figure 4.3: General relationship between exploration results, mineral resources and ore reserves**

The location, quality, grade, geological characteristics and mineral continuity are estimated or interpreted from specific geological evidence and knowledge. According to these properties, mineral resources are subdivided in order of geological confidence: inferred, indicated, and measured resources. The economically mineable part of a measured or indicated mineral resource is then called an ore reserve. The ore reserves are usually assessed during feasibility studies for production decisions. Reserves are subdivided into probable and provable reserves in order of increasing confidence. Probable reserves are the economically mineable part of an indicated mineral resource, and, in some circumstances, measured mineral resources. However, provable resources are the economically mineable part of a measured mineral resource (Moon et al., 2006).
4.3.1.1 Uranium resource terminologies

The NEA and IAEA (2008) classifies uranium resources as either conventional or unconventional. This classification depends on the priority level of the recoverable uranium. Conventional resources are those that have an established history of production and have high grades, where uranium is a primary product, co-product or an important by product (such as from the mining of gold). Subsequently, conventional resources are categorized into identified and undiscovered resources, based on their economic extraction viability and confidence level of their existence. For unconventional resources, uranium is only a minor by-product, such as uranium associated with lignite, phosphate rocks, and from seawater.

The NEA and IAEA (2008) define identified resources as uranium deposits delineated by sufficient direct measurement available to conduct pre-feasibility and sometimes feasibility studies. These consist of reasonably assured resources (RAR) and inferred resources (IR). For RAR, high confidence in estimates of grade and tonnages are compatible with mining decision-making standards. However, for IR, there is a partial degree of confidence in estimates and more direct measurement required before a mining decision is to be made.

Undiscovered resources (prognosticated and speculative) refer to resources that are expected to exist, based on geological knowledge of previously discovered deposits and regional geological mapping. Prognosticated resources are expected to occur in known uranium provinces, supported generally by some direct evidence. Speculative resources are expected to occur in geological provinces that may host uranium deposits. Collectively, prognosticated and speculative resources need more exploration before their occurrence can be confirmed, and grades and tonnages are defined (NEA & IAEA, 2008).

Furthermore, the NEA and IAEA subdivide identified and undiscovered uranium resources into cost categories reflecting the cost of uranium recovered at the ore processing plant in United States dollars (USD): <USD 40/kgU; <USD 80/kgU; <USD 130/kgU. Figure 4.4 shows the relationship between the various resource categories. As
the geological resources knowledge and confidence decreases, the economically feasible extraction of the resource becomes indefinite.

4.3.2 Geographical distribution of uranium resources

4.3.2.1 Identified resources

Uranium deposits are distributed widely in different parts of the world (Figure 4.5), with the largest deposits in Australia, Kazakhstan, Russia, South Africa and Canada. The identified resources at recoverable cost <USD 130/kgU as of January 2007, totalled around 5.5 million tonnes of uranium metal (tU). RAR accounted around for 3.3 million tU, along with around 2.2 million tU for IR (NEA & IAEA, 2008). Table 4.4 shows detailed estimates for RAR and IR for the world’s largest uranium-resource countries.

Figure 4.4: NEA & IAEA classification scheme for uranium resources

(Source: NEA & IAEA, 2008: p. 394)
Most of the countries report only their RAR and IR uranium resources at the <USD 130/kgU recoverable cost category. Surprisingly, the identified resources at recoverable cost categories <USD 40/kgU and < USD 80/kgU are not presented by most of the booming nuclear power and emerging uranium industry countries, such as Finland, Japan, India and Namibia. This is related to confidential data, the fact that assessments are not made within the last five years, and, sometimes, detailed estimates are unavailable. The data for these resource categories should be recognized more and available to increase economic and high geological knowledge confidence. Furthermore, the US does not report resources in the IR category. However, only a few of the world’s largest uranium-resource countries, such as Australia and Canada, report for all the categories (NEA & IAEA, 2008).

Figure 4.5: Global distribution of identified resources (<USD130/kgU)

![Global distribution of identified resources (<USD130/kgU)](image)

Source: (NEA & IAEA 2008: P. 15)
The increase or decrease in reported resources differ between countries on different rates and for various reasons. The most common factors affecting this change in estimated resources are:

- Depletion of resources
- Retirement of mines lifetime
- Closure of mines for shortage of investments
- Notice of uneconomically viable resources after re-evaluation
- New exploration result in new discoveries and increase estimation
- Reopening of mines
- Shift in resources among cost categories, due to uranium market improvement
- Re-evaluation of known deposits (NEA & IAEA, 2008)

### 4.3.2.2 Undiscovered resources

The global estimate of prognosticated resources, as of 1 January 2007, accounted around 2.8 million tU recoverable at < USD 130/kgU, along with 1.9 million tU recoverable at < USD 80/kgU. In the recent years beyond 2005, global uranium estimates of India, Jordan, and the Russian Federation had remarkable increases in their prognosticated resources (NEA & IAEA, 2008).

In India, an increase from 12 100 tU in 2005 to 50 900 tU in 2007 at recoverable cost category < USD 80/kgU was noted. However, in Jordan, it raised from 37 500 tU to 84 800 tU in the < USD 130/kgU category, while there was a threefold increase in Russia, from 56 300 tU to 276 500 tU in the < USD 40/kgU most economically attractive cost category. Simultaneously, Russia’s speculative resources increased from 545 000 tU in 2005 to 714 000 tU in 2007 for the cost category < USD 130/kgU (NEA & IAEA, 2008).
Table 4.4: Global identified resources
(Recoverable resources as of 1st January 2007, (tU), rounded to the nearest 1000 tonnes)
Source: NEA & IAEA (2008)

<table>
<thead>
<tr>
<th>Country</th>
<th>Reasonable Assured Resources</th>
<th>Inferred Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;40USD/kgU</td>
<td>&lt;80USD/kgU</td>
</tr>
<tr>
<td>Australia</td>
<td>709 000</td>
<td>714 000</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>235 500</td>
<td>344 200</td>
</tr>
<tr>
<td>Russia</td>
<td>47 500</td>
<td>172 400</td>
</tr>
<tr>
<td>Canada</td>
<td>270 100</td>
<td>329 200</td>
</tr>
<tr>
<td>South Africa</td>
<td>114 900</td>
<td>205 900</td>
</tr>
<tr>
<td>Namibia</td>
<td>21 300</td>
<td>44 300</td>
</tr>
<tr>
<td>United States</td>
<td>NA</td>
<td>99 000</td>
</tr>
<tr>
<td>France</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Finland</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>China</td>
<td>31 800</td>
<td>44 300</td>
</tr>
<tr>
<td>India</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Japan</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Other</td>
<td>336 300</td>
<td>644 700</td>
</tr>
<tr>
<td>Total</td>
<td>1 766 400</td>
<td>2 598 000</td>
</tr>
</tbody>
</table>

NA: Data not available; NR: Not Reported

Typically, worldwide reporting of speculative resources is limited. The reason given by most countries is that they update evaluations of this type of resource rarely. However, some countries, such as Australia and Namibia, have high uranium resource potential, which is reasonable for them to re-evaluate their resources consistently and report for this category of resource (NEA & IAEA, 2008). It can be said, therefore, that the estimated speculative resources figure 7.7 million tU is uncertain (NEA & IAEA, 2008).
4.3.3 Uranium exploration

Uranium exploration is an economically dependent process. It is directly proportional to uranium spot prices, which, in turn, depend on the supply and demand of uranium for nuclear power generation. This process consumes time, money and effort. As the exploration process is very expensive, it is economically infeasible for uranium exploration and mining companies to invest in this process, unless there is a confidence of gaining a high rate of return. Uranium exploration and development expenditure increases, therefore, at times of high uranium spot prices, which is derived from an under-supply trend (Combs, 2004; Pasco, personal communication.). Most commonly, it takes a decade from the beginning of exploration to the first production (Price et al., 2004). Currently, uranium exploration takes place in sites that are previously known and where there is a high confidence of expected uranium occurrence (NEA & IAEA, 2008).

Several techniques are used to discover new deposits. First, in the area under study, physical properties of its minerals and rocks are measured by using geophysical instruments to detect magnetism, electrical conductivity, and radioactivity, carried out by a helicopter or aeroplane. This initial technique provides hints on what is below the surface, along with indications for specific areas to be explored further on the ground. Secondly, exploration on the ground is carried out by conducting various geochemical, geophysical surveys on samples taken to discover the existence of uranium. In the case of initial positive results in some areas, in particular forests (such as northern Saskatchewan’s Athabasca in Canada), trees lines and branches are cut for further uranium testing. In some instance, trees are cut by hand cut to minimise the environmental impact. Last, drilling - the conclusive exploration method - is applied to examine the existence of economic deposits in the area under study (Areva, 2009).

4.3.4 Uranium supply

Primary uranium production has satisfied about 50-60% of world operating nuclear reactor fuel requirements for almost two decade, as seen in figure 4.6. The remainder
has been met by secondary sources. In 2006, world uranium production (39 603 tU) supplied around 60% of world reactor requirements (66 500 tU) (NEA & IAEA, 2008).

### 4.3.4.1 Uranium production

#### 4.3.4.1.1 Current uranium production status

Uranium production takes place in 20 countries around the world as seen in Table 4.5. In 2008, world uranium primary production totalled about 43 930 tU, of which about 60% was mined in Canada (20%), Kazakhstan (19%), and Australia (19%). Throughout 2008, world uranium production increased by approximately 6% compared with the 2007 world uranium output (41 279 tU). The most significant production increase came from Kazakhstan and Namibia. Table 4.5 shows the historic production of uranium by country (WNA, 2009).

**Figure 4.6 Annual uranium production and requirements (1945-2007)**

Source: (NEA & IAEA (2008), p.74)
Although Canada is maintaining the highest production, it has had a declining rate of production since 2005, due to mining and milling of low grade ores at McClean Lake (the world’s largest producing mine) and Rabbit Lake mines, as a consequence reduced the output (NEA & IAEA, 2008).

However, Australia has lost its world second largest uranium production rank in 2008. The decrease in production is due to processing difficulties at the Olympic Dam mines, high rainfall, which, in turn, restricted the access to the high grade ores at the Ranger mines, and technical difficulties at Beverley mine (NEA & IAEA, 2008).

Kazakhstan was the world second uranium producer in 2008, as it is approaching and targeting to be the world’s largest producer of uranium through doubling the 2008 uranium output by 2010. Furthermore, Kazakhstan has set a production target of 30 000 tU per year to be achieved by 2018, under the perspective of the coming new nuclear renaissance and the expected supply shortage that is likely to happen by 2014 (WNN, 2009b). Currently, its uranium production is growing steadily due to the increase in production at existing mines and new mines.

Alternatively, Namibia has nearly doubled the uranium output throughout 2008, due to the opening of the new Langer Heinrich mine in 2007 (NEA & IAEA, 2008). Namibia is endeavouring to promote the uranium mining industry during the coming decade to enhance its socio-economic development (MME, 2006).

### 4.3.4.1.2 Existing uranium mines

There are around 37 uranium mines operating in the 20 uranium-producing countries around the world. However, most of the production comes from just 11 mines (Table 4.6). In 2008, the most significant production came from the MacArthur River mine in Canada, which produced the largest share (15%) of the world uranium output, followed by the Ranger mine (10%) in Australia (WNA, 2009e).
The most common mining methods used in uranium exploitation are underground and open pit, which were applied in most of the mines in 2008, representing around 62% of methods used. Followed by the in situ leaching (28%), this was applied in Akdala mine in Kazakhstan, with 10% uranium being recovered as by-product. At the Olympic Dam mine in Australia, uranium is recovered with copper, gold, and silver, while gold is recovered in South Africa (WNA, 2009e).

Table 4.5: Uranium production by country (tU)

<table>
<thead>
<tr>
<th>Country</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>% of production 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>11 597</td>
<td>11 628</td>
<td>9 862</td>
<td>9476</td>
<td>9000</td>
<td>20</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>3719</td>
<td>4346</td>
<td>5281</td>
<td>6637</td>
<td>8521</td>
<td>19</td>
</tr>
<tr>
<td>Australia</td>
<td>8982</td>
<td>9512</td>
<td>7593</td>
<td>8611</td>
<td>8430</td>
<td>19</td>
</tr>
<tr>
<td>Namibia</td>
<td>3038</td>
<td>3146</td>
<td>3067</td>
<td>2879</td>
<td>4366</td>
<td>10</td>
</tr>
<tr>
<td>Russia</td>
<td>3290</td>
<td>3285</td>
<td>3190</td>
<td>3413</td>
<td>3521</td>
<td>8.0</td>
</tr>
<tr>
<td>Niger</td>
<td>3185</td>
<td>3322</td>
<td>3443</td>
<td>3153</td>
<td>3032</td>
<td>7.0</td>
</tr>
<tr>
<td>Uzbekistan</td>
<td>2087</td>
<td>2300</td>
<td>2260</td>
<td>2320</td>
<td>2338</td>
<td>5.0</td>
</tr>
<tr>
<td>USA</td>
<td>943</td>
<td>1171</td>
<td>1805</td>
<td>1654</td>
<td>1430</td>
<td>3.0</td>
</tr>
<tr>
<td>Ukraine</td>
<td>855</td>
<td>830</td>
<td>808</td>
<td>846</td>
<td>800</td>
<td>2</td>
</tr>
<tr>
<td>China</td>
<td>730</td>
<td>750</td>
<td>750</td>
<td>712</td>
<td>769</td>
<td>2</td>
</tr>
<tr>
<td>South Africa</td>
<td>747</td>
<td>673</td>
<td>534</td>
<td>539</td>
<td>655</td>
<td>1</td>
</tr>
<tr>
<td>Brazil</td>
<td>159</td>
<td>110</td>
<td>200</td>
<td>299</td>
<td>330</td>
<td>1</td>
</tr>
<tr>
<td>India</td>
<td>230</td>
<td>230</td>
<td>230</td>
<td>270</td>
<td>271</td>
<td>1</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>412</td>
<td>409</td>
<td>375</td>
<td>306</td>
<td>263</td>
<td>1</td>
</tr>
<tr>
<td>Romania</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>77</td>
<td>77</td>
<td>0.2</td>
</tr>
<tr>
<td>Germany</td>
<td>77</td>
<td>94</td>
<td>65</td>
<td>38</td>
<td>77</td>
<td>0.2</td>
</tr>
<tr>
<td>Pakistan</td>
<td>38</td>
<td>40</td>
<td>40</td>
<td>45</td>
<td>45</td>
<td>0.1</td>
</tr>
<tr>
<td>France</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>0.01</td>
</tr>
<tr>
<td>Others</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>40 188</td>
<td>41 943</td>
<td>39 603</td>
<td>41 279</td>
<td>43 930</td>
<td></td>
</tr>
</tbody>
</table>

Source: (NEA & IAEA, 2008; WNA, 2009)
Most of these mines are privately owned by domestic and non-domestic mining companies. The world’s major producing mine - McArthur in Canada is mainly operated and owned by the Canadian mining company Cameco, with a 30% share of the French mining company Areva Resources. The new Inkai mine in Kazakhstan, which is expected to start production by the end 2009, is owned and operated by Joint Venture Inkai (JVI) which is owned by Cameco (60%) and the Republic of Kazakhstan government-owned mining company KazAtomProm (40%). In contrast, all Russian Federation mines are 100% owned and operated by the government-owned uranium mining company ARMZ (NEA & IAEA, 2008; Cameco, 2009; WNA, 2009e).

### Table 4.6: Largest producing uranium mines in 2008

<table>
<thead>
<tr>
<th>Mine</th>
<th>Country</th>
<th>Main Owner</th>
<th>Type</th>
<th>Date of first production</th>
<th>Production tU/year</th>
<th>% of world</th>
</tr>
</thead>
<tbody>
<tr>
<td>McArthur</td>
<td>Canada</td>
<td>Cameco</td>
<td>Underground</td>
<td>1999-2013</td>
<td>6383</td>
<td>15</td>
</tr>
<tr>
<td>Ranger</td>
<td>Australia</td>
<td>ERA(Rio Tinto)</td>
<td>Open pit</td>
<td>1981</td>
<td>4527</td>
<td>10</td>
</tr>
<tr>
<td>Rossing</td>
<td>Namibia</td>
<td>Rio Tinto (69%)</td>
<td>Open pit</td>
<td>1976</td>
<td>3449</td>
<td>8</td>
</tr>
<tr>
<td>Olympic Dam</td>
<td>Australia</td>
<td>BHP Billiton</td>
<td>By-product/underground</td>
<td>1988</td>
<td>3344</td>
<td>8</td>
</tr>
<tr>
<td>Kraznokamensk</td>
<td>Russia</td>
<td>ARMZ</td>
<td>Underground</td>
<td></td>
<td>3050</td>
<td>7</td>
</tr>
<tr>
<td>Arlit</td>
<td>Niger</td>
<td>Areva/Onarem</td>
<td>Open pit</td>
<td></td>
<td>1743</td>
<td>4</td>
</tr>
<tr>
<td>Rabbit Lake</td>
<td>Canada</td>
<td>Cameco</td>
<td>underground</td>
<td>1975</td>
<td>1368</td>
<td>3</td>
</tr>
<tr>
<td>Akouta</td>
<td>Niger</td>
<td>Areva/Onarem</td>
<td>underground</td>
<td>1974</td>
<td>1289</td>
<td>3</td>
</tr>
<tr>
<td>McClean Lake</td>
<td>Canada</td>
<td>Areva</td>
<td>Open pit</td>
<td>1999</td>
<td>1249</td>
<td>3</td>
</tr>
<tr>
<td>Akadala</td>
<td>Kazakhstan</td>
<td>Uranium One</td>
<td>ISL</td>
<td>2006</td>
<td>1034</td>
<td>2</td>
</tr>
<tr>
<td>Beverley</td>
<td>Australia</td>
<td>Heathgate Resources</td>
<td>ISR</td>
<td>2000</td>
<td>1000</td>
<td>2</td>
</tr>
</tbody>
</table>

Source: WNA (2009e)
4.3.4.1.3 New uranium mines

There are several new uranium mines around the world, and it is mainly in the current 20 uranium-producing countries where they are planned, proposed, and under construction, with various starting operation dates projections, beginning at end of 2009 up to 2030 (Appendix 1). This is in addition to expansion plans and proposals of existing mines (Appendix 2), such as the Olympic Dam and Ranger mines in Australia, McArthur River and Key Lake mines in Canada, which have just renewed their operation licences up till 2013 (NEA & IAEA, 2008). Table 4.7 includes the major uranium mines envisaged in specific plans, proposals, and expected to be operating by 2030 and beyond.

Table 4.7 World’s major expected uranium mines

<table>
<thead>
<tr>
<th>Mine</th>
<th>Country</th>
<th>Main Owner</th>
<th>Type</th>
<th>Status</th>
<th>Date of first production</th>
<th>Estimated Production (tU/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inaki</td>
<td>Kazakhstan</td>
<td>Cameco</td>
<td>ISL</td>
<td>Under development</td>
<td>2009</td>
<td>192</td>
</tr>
<tr>
<td>Honeymoon</td>
<td>Australia</td>
<td>Uranium One</td>
<td>ISR</td>
<td>Under development</td>
<td>2010</td>
<td>340</td>
</tr>
<tr>
<td>Four Mile</td>
<td>Australia</td>
<td>Quasar Resources Pty Ltd</td>
<td>ISL</td>
<td>Under development</td>
<td>2010</td>
<td>1400</td>
</tr>
<tr>
<td>Cigar Lake</td>
<td>Canada</td>
<td>Cameco (50%)</td>
<td>Underground</td>
<td>Under development</td>
<td>2011</td>
<td>6900</td>
</tr>
<tr>
<td>Olympic Dam Expansion</td>
<td>Australia</td>
<td>BHP Billiton</td>
<td>By-product/ Open pit</td>
<td>proposed</td>
<td>2019 (estimated)</td>
<td>12 720</td>
</tr>
<tr>
<td>Midwest</td>
<td>Canada</td>
<td>Areva</td>
<td>Open pit</td>
<td>postponed</td>
<td>-</td>
<td>2300</td>
</tr>
</tbody>
</table>

Source: (WNA, 2009e; BHP Billiton, 2009; WNA, 2007; Cameco, 2006)

The Honeymoon mine was proposed to start operation in 2008, but has been delayed to mid-2010. This delay is due to a sudden increase in the capital cost and the economic
crisis that started in 2008, which, in turn, led to the suspension of the mine development in May 2008, until a new partner joined the development process in October 2008 and resumed the project (Advertiser, 2008).

In the Four Mile mine, a feasibility study is under progress to examine the economic viability of utilizing electricity from a geothermal plant near the site. This anticipation will make the mine the first uranium mine in the world to meet its electricity needs from a renewable energy source (Uranium Weekly, 2009).

The Cigar Lake mine, which has the world’s largest undeveloped uranium grade deposit - at an average grade 20.7% - was planned to begin production in 2007. However it was flooded in October 2006 due to an unexpected technical incident followed by a rock fall, which, as a consequence, stopped the construction on site for access difficulties, since it is an underground mine. It is now under remediation and production is not expected until at least 2011(Cameco, 2006).

The proposed Olympic Dam expansion is aspiring to raise the current production by four times to 12 720 tU per year, for an estimated production period of 40 years. This proposed expansion is considered to be a progressive development, requiring construction activity over a period of 11 years (BHP Billiton, 2007).

The proposed construction is to build new minerals processing facilities infrastructure, including a coastal desalination plant, a new power line and possibly a gas-fired power station, a rail line, an airport, port facilities, a village to accommodate workers, and more housing, retail, commercial and community facilities in Roxby Downs (BHP Billiton, 2007).

The project schedule will depend, ultimately, on the timing and nature of government approvals, along with the final investment decision of the owning and operating company, BHP Billiton Board (BHP Billiton, 2009).

The development in the Midwest mine has been postponed without providing new dates for resuming. However, the environmental assessment of the project will be completed
for future considerations. It was expected to begin production in 2010, but the current
global economic downturn and the current low uranium prices have delayed its
development. The increasing capital and operating costs have affected the capital
expenditures (Mining Top News, 2008). This in fact is considered economically
unfeasible investment and unprofitable, which in turn, led to the impediment to the
project’s progress.

4.3.4.2 Secondary sources

These are nuclear fuel sources that are not supplied directly from the natural uranium
production process. These are civilian and military stockpiles and inventories, mixed-
oxide fuel (known as MOX fuel), reprocessed uranium (RepU), and re-enrichment of
depleted uranium. Currently, these secondary supplies have a significant contribution in
meeting the nuclear reactors annual fuel demand. However, the availability of these
sources, excluding MOX fuel, is diminishing, since the stockpiles and inventories are
running out (SDC, 2006; ESA, 2007; NEA & IAEA, 2008).

4.3.4.2.1 Uranium stocks and inventories

During the period from the late 1950s until 1990, and in particular the mid-1970s, there
was an excessive oversupply of uranium. This was due to overestimated projections of
nuclear power generation growth rate and military requirements. This, in turn,
overestimated the uranium requirements and led to more uranium production than was
certainly needed.

As uranium can be stored long term, this excess in uranium production created a
stockpile of uranium available for future use in commercial nuclear power reactors for
electricity generation. This was purchased by governments and nuclear power utilities.
In addition, most of the utilities have their own policies in holding a strategic stock,
along with a pipeline inventory that is equivalent to 1-2 years of natural uranium
requirements (NEA & IAEA, 2008).
There are insufficient data on the magnitude and actual size of these inventories and stockpiles available. The reason for that is most countries do not report information on stockpiles held by their utilities and governments, since it is considered a matter of confidentiality in maintaining national security (NEA & IAEA, 2008).

4.3.4.2.2 Highly enriched uranium from the Russian Federation

In 1992, the governments of the US and the Russian Federation signed the Highly Enriched Uranium (HEU) purchase agreement for the disposition of HEU extracted from the Russian nuclear weapons. The HEU agreement allows the US government to purchase 500 tonnes of HEU converted to commercial grade Low Enriched Uranium (LEU) from the Russian Federation over a period of 20 years (1994-2013) for use in domestic commercial nuclear power plants. The HEU agreement deliveries are a substantial source of adequate supply in meeting the US uranium requirements at affordable prices (DOE, 2007).

Since 1994, about 332 tonnes of HEU had been received by the US until the end of 2007. In order to reach the total goal of 500 tonnes of HEU, around 30 tonnes of deliveries have been scheduled annually from 2008 to 2012. This annual amount is equivalent to approximately 9000 tonnes of natural uranium, which represents around 13% of the world’s annual uranium requirement, based on 2006 figures. After the expiry of the HEU agreement, the Russian Federation is anticipated to export LEU to meet around 20% of the US annual uranium demand between the periods 2014-2020, under the amended 2008 US-Russian suspension agreement. In addition, smaller quantities of imported Russian LEU or the product equivalent over the HEU agreement deliveries would be permitted during the period 2011-2013 (DOE, 2007).

4.3.4.2.3 Mixed oxide fuel (MOX)

This is an artificial nuclear fuel consisting of a mixture of plutonium oxide and uranium oxide mixed together to be used in nuclear reactors to generate electricity. It is manufactured from the plutonium of reprocessed spent fuel along with the depleted
uranium left over from the primary natural uranium enrichment process (Bodansky, 2004; SDC, 2006).

MOX merely reduces the demand for primary uranium fuel and does not displace it (SDC, 2006). It is argued that the production of MOX fuel provides reduction in the volume and toxicity of the reactor spent fuel and depleted uranium (WNA, 2009f). Given that, the output of reprocessing of spent fuel – plutonium - is used in the formation of nuclear bombs, which is considered an attractive material for theft by terrorists. This may increase the security risk in the case of misuse or theft, since its protection and its peaceful use may not be 100% guaranteed (NCI, 2009a). Furthermore, in the case of a nuclear plant accident, a plutonium-fuelled reactor has a twice the potential to cause severe cancer more than a reactor fuelled with just uranium (NCI, 2009a). Public security, health and safety implications, as a consequence of using MOX fuel, need to be given higher priority over its potential as a nuclear fuel supply. However, as a part of this thesis, the main focus is on examining the MOX fuel supply potential as an alternative nuclear fuel and its impact on the uranium supply.

The availability of MOX fuel is due to the excess of plutonium kept by governments from previous reprocessing of spent fuel and from surplus weapons related plutonium, and their intention to get rid of it (personal communication). In 2006, MOX fuel supply represented around 2% of the total supplied nuclear fuel, with production capacity of around 300 tonnes per year (t/yr) (SDC, 2006). Currently, the world MOX fuel production capacity is approximately 200t/yr (WNA, 2009f). The MOX fuel fabrication capacities are limited, with one plant in France, whose capacity has risen recently, from around 145t/yr to 195t/yr, and one in the UK that is suffering from operational difficulties, which resulted in reduced capacity from 128t/yr to 40t/yr. In 2006, the 40t/yr MOX fuel fabrication plant in Belgium was closed. Japan is planning to commission a 130t/yr in 2011 (NEA, 2008 p.404). There are no further plants under construction for future expansion.

Globally, the use of MOX fuel is currently limited to around 33 reactors in Belgium, France, Germany, India, and Switzerland (NEA & IAEA, 2008). The existing reactors
accommodate only about a one-third fraction of MOX in the reactor core, with the remainder primary produced uranium, due to the difference in nuclear properties of plutonium and uranium (Bodansky, 2004).

However, MOX fuel is commercially undesirable as it is very expensive, due to the existence of plutonium, which makes it difficult and extremely expensive to handle. MOX fuel is not as easy to manage as uranium, in which robots are used to handle it since it requires remote handling (Thomas, personal communication). It is more difficult technically to control the thermal reactor loaded with plutonium than that with uranium only (Bodansky, 2004). Moreover, MOX fuel has a negative impact on the operation and maintenance of the nuclear reactor, since plutonium contaminates the reactor, which in return, requires more cleaning than is regularly done and increasing the maintenance cost for employing more individuals for maintenance. Furthermore, MOX fuel raises the decommissioning cost of the reactor for being more contaminated (Thomas, personal communication).

MOX fuel may only be reliable if the uranium prices increased dramatically; in which this may not happen throughout the life time of the coming nuclear renaissance since uranium prices have no significant impact on the economics of nuclear power (Thomas, personal communication). Furthermore, the shift to 100% fully loaded MOX fuel cannot be accomplished in most of the conventional LWRs, only new designed reactors such as EPR and AP1000 are able to accommodate full load of MOX fuel (WNA, 2009f), in which none of the existing or under construction reactors are of these types. MOX fuel is, therefore, not seen to be a substantial nuclear fuel alternative.

4.3.4.2.4 Reprocessed uranium (RepU)

It is recovered uranium from reprocessing of spent nuclear fuel; however, its recycling is economically unfeasible. The RepU is too radioactive to be handled in fuel fabrication plants at the current state of technology (Storm Van Leeuwen, 2007b). The recycling of RepU is enormously expensive, since it requires much more enrichment than that required for natural uranium (WNA, 2009a).
It was previously utilized in Belgium and Sweden. At present, RepU is used with declining rate in Japan and Switzerland. However, France has a steady rate of consumption. It has demonstrated the use of RepU fuel in its 900 MW reactor cores for further utilization. It found that it is currently uneconomically viable for deploying it, due to the high enrichment required and dedicated facilities needed for handling of RepU due to gamma radiation emitted from U-232. The UK has reprocessing facilities however; it does not report any data on produced or consumed RepU (NEA, 2008; NEA & IAEA, 2008).

The 2008 ‘Red Book’ noted that there is very limited information available concerning how much RepU is used, based on the available data that RepU represents less than 1% of projected world requirements annually (NEA & IAEA, 2008). Thus, it can be concluded that RepU has no substantial contribution to the current nuclear fuel supply or any projections for its use in the future.

4.3.4.2.5 Re-enriched depleted uranium tails

Depleted uranium is a part of the output of the enrichment process, which can be re-enriched and used in nuclear reactors as a fuel to conserve natural uranium reserves. There are around 1.2 million tonnes of depleted uranium stocks worldwide (WNA, 2007). At present, it is uneconomically viable to re-enrich depleted uranium in large quantities. It is only economic in centrifuge enrichment plants that have spare capacity, which in fact not available and low operating costs (NEA & IAEA, 2008).

Similarly, however, the data regarding the production and use of re-enriched depleted uranium are restricted. The information available in the 2008 ‘Red Book’ indicates that Russia re-enriches a small amount of tails and exports to the EU, in a declining rate (Table 4.8). In 2006, however, Russia announced that no more deliveries will take place after the expiry of the existing contracts. In addition, Finland is the only country using re-enriched uranium; Belgium had used it previously.
Table 4.8: Russia’s supply of re-enriched depleted uranium to the European Union

<table>
<thead>
<tr>
<th>Year</th>
<th>Re-enriched depleted uranium deliveries(tU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>1 050</td>
</tr>
<tr>
<td>2002</td>
<td>1 000</td>
</tr>
<tr>
<td>2003</td>
<td>1 200</td>
</tr>
<tr>
<td>2004</td>
<td>900</td>
</tr>
<tr>
<td>2005</td>
<td>500</td>
</tr>
<tr>
<td>2006</td>
<td>700</td>
</tr>
</tbody>
</table>

Source: NEA & IAEA (2008)

4.4 Uranium market

4.4.1 Background

Uranium trade is unlike other mineral commodities, such as tin, copper and aluminium, whose trade is on an open market, such as the London Metal Exchange. Uranium, rather, is most commonly sold through private contracts and negotiations between sellers (mining companies) and buyers, such as power utilities, on the basis of long-term contracts from 3-7 years and more. These contracts are private documents and their contents are not in the public domain. Alternatively, it is sold on day-to-day marginal trading in which the existing uranium spot prices at the time of purchase are applied to it. Prices are published by independent market consultants Ux Consulting or TradeTech ( Cameco, 2009a; WNA, 2009a).

Globally, uranium is typically traded in US dollars per pound of uranium oxide (US $/lb U₃O₈); in other words, the yellowcake. It is also sold in the form of converted uranium UF₆, enriched uranium and the fabricated fuel rods. In addition, there is trade of spent fuel rods for use in the reprocessing process. However, its international trade is not published for political reasons (BGS, 2007).

The uranium produced by Australia, Kazakhstan, Namibia, Niger and Uzbekistan is exported, since these countries do not pursue nuclear power generation. Conversely, the largest nuclear power generators, such as the US, Japan and France depend mainly on imported uranium. Several countries may be involved in the supply chain. For example,
uranium as yellowcake may be mined and purchased from a country such as Namibia, converted in France, enriched in Russia, fabricated into fuel rods in Germany and, finally, installed in various reactors in Finland. Furthermore, uranium may be mined in a nuclear power-generating country, but is transferred to other countries for fuel facilities, and returns back as fuel rods for use in the reactors, for example, in Brazil or South Africa. This is due to limited restrictions set by the IAEA on establishing nuclear fuel facilities to limit the widespread of material may be of use in the formation of nuclear weapons (BGS, 2007).

The trade in uranium is monitored, and the purpose of which how uranium will be used is inspected. The IAEA undertakes audits of the trade in uranium, along with inspections of nuclear facilities, in order to ensure compliance with the conditions of the Nuclear Non-Proliferation Treaty (NPT). The purpose of these measures is to ensure that uranium is used for civilian energy purposes and not diverted into weapons (BGS, 2007).

4.4.2 Uranium price history

4.4.2.1 Uranium prices from late 1960s to late 1970s

A non-military market for uranium developed in the late 1960s in response to the demand for meeting the growing nuclear power reactors for generating electricity in various countries. Figure 4.7 shows the history of uranium spot prices.

The commercial uranium market started with low uranium prices - spot prices were within the rage of $5.50 – 7/lb U3O8 - due to the reduced demand for uranium at this period of time. This was a consequence of the availability of uranium stocks kept by governments and industry inventory schemes that resulted from excess capacity due to reduction of military requirements. These depressed uranium prices remained relatively constant until the end of 1973 (Radetzki, 1981).

Consequently, electric utilities were discouraged to place long-term contracts. A number of uranium producers were unable to manage their production costs within these poor
market conditions, as there were no reasonable profits in return. This led several producers to leave the business. The anticipation of prices improvement, due to the prospect of future growing demand for nuclear power, and the prospect of the revival of military demand was the main motivation for those who remained in the industry. Despite that there was limited production, along with low rate of return, the perception of market improvement led to exploration for new uranium deposits and development of uranium drilling in several countries, such as Australia and Canada (Radetzki, 1981).

From 1974-1976, uranium spot prices increased rapidly - by almost six times of the 1973 prices, from about $8 to around $42/lbU₃O₈ - as well as long-term contract prices. These spot prices continued to increase from late-1976 until mid-1978 at a far more moderate rate than in the three previous years. It then remained almost stable within a range of $42-44/lbU₃O₈ until late 1979 (Radetzki, 1981).

This rigorous change in the market resulted in uranium producers renegotiating the old long-term contracts with their customers, whereby the future deliveries low prices that were agreed upon in the past, were increased. Though, this condition was not in the European contracts, it was just found in the US contracts (Radetzki, 1981).

4.4.2.1.1 Factors affected the mid 1970s uranium prices explosion

During the 1970s, the explosion in uranium prices was considered a unique incident, having never happened before in the history of any other significant commodities, except for oil. Some of the factors that enforced this explosion were criticized for being unusual (Radetzki, 1981). There were several factors beyond and after the pivotal year of 1973 that enforced the rapid uranium price escalation.

The marked increase in uranium prices was initiated by the unstable oil market in the early 1970s, which ended with the 1973 oil crisis, which led to the decision to expand nuclear power programmes in several countries, such as France, Japan and Germany. There was, therefore, an exaggerated projection for future uranium requirements, along with the extra demand ordered by the US nuclear surge. This created the belief that there might be a supply shortage, since there were uncertainties over the availability of
sufficient supply. Australia Canada and France announced that there might be limited uranium available for export, and, in some instances, there might not be any, due to new domestic policies. The delay in the operation of reprocessing technology of spent fuel - due to technical; environmental; regulatory and financial difficulties - increased the scarcity of uranium supply. Furthermore, the shortage in US enrichment facilities to meet any growing demand led several countries to maximize their orders for future considerations. The 1972 uranium cartel was created to compete with US uranium prices, and to raise prices that had been disrupted for several years. It was said that this cartel was the main driver for the flawed decisions made by the governments at this time (Buckley et al., 1980; Radetzki, 1981).

Figure 4.7 Average Uranium Spot Prices from 1948 - 2007

Source: (Kee, 2007: p.59)
By the end of 1970s, uranium prices began to decline. The scare of uranium shortage started to diminish, due to the lower growth in electricity demand caused by slower economic growth and expensive electricity production, along with licensing delays, long construction procedure and nuclear power high capital costs. These issues reduced the rate of nuclear power plants ordering from 1975 onwards. In addition, the uranium cartel was banned in 1975, and most uranium production and export policies were reformed (Buckley et al., 1980).

4.4.2.2 Uranium prices during the 1980s

Following 1980, uranium spot prices were in continuous decline for two years, though it did not reach the prices prior to 1974. Uranium spot prices kept fluctuating within a narrow range of low values for almost two decades (1983-2000), where it reached to the minimal value of around US $ 7.10/Ib U₃O₈ late 2000 only. Despite the Three Mile Island and Chernobyl accidents in 1979 and 1986 respectively, there was no noticeable steep decline or increase in spot prices, as had happened previously in the 1970s. The reason for low uranium prices was low uranium demand and the availability of secondary sources that met around 40% of the global annual demand (Comb, 2004).

4.4.2.3 Uranium prices during the 2000s

Spot prices began to rise slowly by the beginning of 2001 until mid-2003, where it was about $11/Ib U₃O₈. It then accelerated much more rapidly, reaching around US $ 48/Ib U₃O₈ three years later. In April 2007, uranium spot prices exceeded US $100/Ib U₃O₈ when it jumped to a historic price of US $ 139/Ib U₃O₈ in June 2007, and then declined again to reach US $ 90/Ib U₃O₈ at the end of 2007 (NEA, 2008).

The dramatic rise in uranium spot prices during 2006 and 2007, and in particular the steep increase that happened in mid-2007, was driven partly by limited supply and demand correlation, and the flooding of two major uranium mines in Canada (Cigar Lake in 2006) and Australia (Ranger Mine in early 2007), which created a prospect of limited uranium production. Uncertainties over diminishing uranium stockpiles and the
expiry of the US-Russia HEU agreement in 2013, helped create scares of supply shortage at a time of anticipated growing nuclear power (DOE, 2007; Olsen, 2007; NEA, 2008).

Since then, uranium spot prices decreased until mid-2008 and started fluctuating within the range of US $ 45 – 55 /lb U₃O₈, reached US $ 47/lb U₃O₈ in August 2009 (Cameco, 2009a; Ux Consulting, 2009).

In summary, the uranium market appears to be less transparent than others. Throughout the history of the uranium market, the relationship between supply and demand is not the only factor controlling uranium spot prices, or even the negotiated long-term contract prices from the available data, since long-term contracts are confidential documents and not publically available. Deviation in other energy commodity prices due to an unstable climate in international politics had an impact on uranium spot prices during the mid-1970s. The long-term storage facility of uranium either yellowcake or enriched uranium, and the involvement of governments by their military stocks, have been the main constraints in pushing uranium prices down for almost two decades.

4.5 The cost of nuclear fuel

The cost of raw uranium is around a quarter of the nuclear fuel cost loaded into a nuclear reactor. The remainder is mostly the cost of enrichment and the fuel fabrication (WNA, 2008c).

In January 2007, the nuclear fuel cost was approximately US $ 1787/kg (at uranium contract price ~ US $53/ kgU₃O₈) (WNA, 2008c). The following is a detailed example of the cost of 1 kg of nuclear fuel (WNA, 2008c):

Cost of uranium = 8.9 kg U₃O₈ x $53 = $ 472
Cost of conversion = 7.5 kgU x $12 = $ 90
Cost of enrichment = 7.3 SWU x $135 = $ 985
Fuel fabrication per kg = $240
Total cost (approximately) = US $1787
Numerous nuclear power economists argue that the price of raw uranium (yellowcake) is insignificant to the total cost of nuclear electricity generated, since the cost of raw uranium is around 5% of the total price of the power produced (Uranium Stocks, 2007; Thomas, personal communication). Consider the following example. If the January 2007 uranium spot price (US $ 72/lb $U_3O_8$) is doubled, then the cost of total power generated may increase by 5%. This is seen to be an incentive for expansion of nuclear power, so that, ‘the uranium would remain “affordable“ even with large increase in uranium prices’ (Bodansky, 2004: p. 221).

The effect of uranium prices’ fluctuation is considered to have a relatively minor effect in the total cost of electricity generated, in comparison with other energy commodities, such as oil. If the price of oil is doubled, then the cost of the electricity generated will increase by 40%, since the cost of oil represents around 40% of the final total cost of the generated power in an oil power station (Uranium Stocks, 2007).

The increase in fuel burn up rate\(^2\) within the limit allowed by design and licensing has a slightly significant effect on the reduction of nuclear fuel cost. It leads to less frequent shutdown of the plant for refuelling, which, as a consequence improves the energy availability factor and helps in saving the nuclear fuel needed (NEA, 2008). A further 8% increase in burn-up will provide a 5% reduction in fuel cost (WNA, 2008c). A high burnup requires a high initial enrichment in U-235, though (NEA, 2008).

This chapter has addressed the current and the projected status of nuclear power generation and uranium supplies. It has presented the geographical distribution of uranium identified resources and production. It has presented the history of uranium market since its initiation in the late 1960s until now. This chapter concludes that primary uranium production has never met 100% of global annual uranium demand for around 20 years. The involvement of uranium secondary sources, in particular uranium inventories and stockpiles and the US – Russia HEU agreement, have been the main

\(^2\) Fuel burn up rate is the energy obtained per unit mass of fuel. Commonly specified in megawatt-days or gigawatt-days of thermal output per metric tonne of heavy metal (MWDT/MTHM or GWDT/MTHM) (Bodansky, 2004: p.206).
reason leading to unstable uranium market, enforcing low uranium prices and inhibiting any new investment for new exploration of uranium deposits. However, it is expected that these secondary sources will be depleted by 2013. The role of MOX fuel, RepU, and re-enrichment of depleted uranium tails is limited and may not have a significant contribution in the next two decades.
CHAPTER 5
DISCUSSION

5.1 Introduction

According to most of the literature, the remaining lifetime of uranium resources varies from thirty to hundreds and thousands of years, yet there is agreement on the rate of consumption, approximately 65,000 tU/yr. This is presented in Table 5.1.

Table 5.1: Uranium lifetime interpretations

<table>
<thead>
<tr>
<th>Source</th>
<th>Lifetime Availability (years)</th>
<th>Assumed consumption rate (tU/yr)</th>
<th>Type of resources</th>
<th>Amount of resources (estimates)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUA, 2008</td>
<td>&gt; 100</td>
<td>67 000</td>
<td>Identified Resources</td>
<td>-</td>
</tr>
<tr>
<td>Bodansky, 2004</td>
<td>80</td>
<td>(4x 60 000 tU/yr) ~ 240 000 tU/yr</td>
<td>Identified and undiscovered resources</td>
<td>20 Mt</td>
</tr>
<tr>
<td>ESA, 2007</td>
<td>85</td>
<td>66 500</td>
<td>Identified Resources</td>
<td>-</td>
</tr>
<tr>
<td>ESA, 2007</td>
<td>300</td>
<td></td>
<td>Conventional Resources</td>
<td>16 872 700 tU</td>
</tr>
<tr>
<td>EWG, 2006</td>
<td>30</td>
<td>67,000</td>
<td>RAR(&lt;$40/kgU)</td>
<td>-</td>
</tr>
<tr>
<td>NEA &amp; IAEA, 2008</td>
<td>~ 100</td>
<td>66500</td>
<td>Identified Resources</td>
<td></td>
</tr>
<tr>
<td>Paul Mobbs, 2005</td>
<td>42</td>
<td>67 000</td>
<td>Known Resources(Identified)</td>
<td>2.8 Mt</td>
</tr>
<tr>
<td>Price and Blaise, 2002</td>
<td>Hundreds, Thousands of years</td>
<td>-</td>
<td>Conventional and unconventional resources</td>
<td>-</td>
</tr>
<tr>
<td>WNA, 2008</td>
<td>80</td>
<td>65 000</td>
<td>Known economic resources*</td>
<td>5.5 Mt</td>
</tr>
</tbody>
</table>

Source: Based on personal collected data
* Known economic resources defined by WNA (2008b) as ‘the world’s present measured resources of uranium (5.5 Mt) in the cost category somewhat below present spot prices and used only in conventional reactors.’

It is certain that, if the rate of consumption is increased, then uranium availability will decrease. So, if it is assumed by the NEA and IAEA (2008) that the uranium requirements will double by 2030, uranium will be depleted at a range of 15-150 years at a fixed geological level of knowledge and confidence.

This wide range in estimates of the remaining years of uranium is a consequence of various prospects addressing the uranium level of geological knowledge and confidence. The longest estimates of uranium availability are based on all conventional and unconventional resources, while from the shortest are based on just the RAR at a cost category less than $40/kgU.

This reflects the conflict between the two different perspectives addressing the availability of uranium resources, the first depends on economic availability (which was originally conducted from Hotelling’s rule from 1931) and the second is based on physical availability.

The economic view argues that finite resources are substitutable, as long as, the mineral market price is high enough to encourage investment in its exploration and exploitation process (Pearce & Turner, 1990). Numerous economists argue that resource costs and prices trends are better than the physical measures for determining long-term resource scarcity (MacDonald, 2003). However, this economic view is to some extent practically unfeasible because, as Storm Van Leeuwen (2007b) points out, the physical quantities and physical boundaries – such as the energy input limit per unit product – are not considered in the economic view.
5.2 Economic measures

In well functioning minerals and energy commodities markets, prices can be a significant indicator of the conditions that prevail in a market. Prices reflect the supply and demand relationship, and are considered to be a measure of economic impacts. In addition, price trends may provide evidence for predictions of scarcity and depletion of minerals or energy resources (Radetzki, 1981; Combs, 2004; MacDonald, 2003; Kruyt et al., 2009).

This, however, is not the case with uranium market. Uranium spot prices have never been good indicators for supply-and-demand balancing mechanisms, nor have they exhibited what level of production the mining industry has attained. Combs (2004) argues that uranium spot prices indicate different situation than that typically given in similar conditions in other successful markets.

The uranium market is unique in comparison to other markets due to its imbalanced relationship between production and consumption. The availability of the secondary sources – in particular the uranium inventories – has had the major impact of causing low uranium prices for many years. In addition, these depressed prices suppressed the production and exploration efforts. Consequently, the price trend has often failed to reflect the relative scarcity of uranium supplies (Comb, 2004).

Moreover, the misleading indications of the interaction between supply and demand and market prices makes it difficult to assess the uranium primary production rate - flexibility or firmness - in respect to uranium prices. Thus, making it difficult to predict the future uranium market.

5.3 Physical measure

The assessment of the availability of uranium resources for ensuring future security of nuclear fuel supplies should be based on discovered resources, where its geological and mineralogical evidence are known and confirmed. Production of uranium cannot be implemented unless there are discovered resources. The NEA and IAEA (2008) state
that the undiscovered resources are ‘the resources that are expected to occur based on geological knowledge of previously discovered deposits and regional geological mapping’; and ensures that these types of resources ‘require significant amounts of exploration before their existence can be confirmed and tonnage can be defined’ (NEA & IAEA, 2008: p.24). There is a possibility, therefore, that these undiscovered resources, which are taken into consideration for ensuring future security of supplies, may not occur because their existence is still unknown. In addition, the chances of finding new major discoveries are limited (Storm Van Leeuwen, personal communication).

Despite the fact that the element uranium is abundant in the Earth’s crust in many types of rocks from granite to sedimentary, and in sea water, the extent to which the methods extraction and exploitation methods are economically viable using today’s technology is a crucial aspect in assuring uranium availability. Although high uranium prices stimulate more exploration leading to new discoveries, these discoveries might be of low quality with small ore body; low grade or at a deep depth and difficult to mine. The majority of the high quality resources that are easily accessible and easily mined have already been discovered and are in production (Storm Van Leeuwen, personal communication). In addition, there has been no published data indicating new major high grade deposits discoveries in the past two decades (Storm Van Leeuwen, 2007b). Extraction of lower grade quality uranium requires more energy than that needed in the extraction of high-grade uranium ores, which yields less net energy produced from the output of the nuclear energy system (figure 5.1). The energy balance of the complete nuclear energy system becomes zero at grades level below 0.02%U (Storm Van Leeuwen, personal communication). Currently, the world average uranium ore grade is around 0.15% U₃O₈, which is on the edge of the energy cliff. Thus, the possibilities of finding high-grade ores seem to be small (Storm Van Leeuwen, 2008a). Storm Van Leeuwen (2008a) suggests that it would be worthwhile exploring for new uranium deposits of grades more than 0.03% U₃O₈.
5.3.1 Reserve to production ratios indicator

It may be unreliable to apply the reserves to production ratios (R/P ratios or RPRs), as in estimates of lifetimes of gas and oil reserves, to that of uranium. R/P indicates the years of production left at the current production rate, which are often used as an indicator for security of supply (Kruyt et al., 2009). The current rate of production is not the actual potential of the uranium industry. This is because the current production rate meets about 60% of the global annual uranium demand, which is caused by the presence of secondary sources that meet the remaining 40%. Consequently, this makes it difficult to reference the current production rate in order to measure the available uranium reserves. The use of any of these figures of projected production levels, uncertain reserve estimates, and rapidly changing demand, produce uncertain and ambiguous reserves to production ratios (Kruyt et al., 2009).

5.4 Uranium production

Global uranium production capability plays a significant role in the scarcity of uranium supplies as a nuclear fuel. This thesis views it as the main link between high-energy uranium resources’ availability and nuclear fuel supply. It is essential, therefore, to examine the global production potential for critical assessment. This point is acknowledged here by studying the current two major uranium producing countries and the two anticipated future significant producers.

The uranium production rate is in decline in two Canada and Australia, due to various constraints discussed earlier in Chapter 4. Some of these are technical and operational difficulties; natural disaster, including flooding and rainfalls; and mining of low-grade mines.

Similarly, the development of some new mines in Canada and Australia are almost facing similar barriers as current operating mines. Both the exploitation of the most Canada’s Cigar Lake mine and the expansion of Australia’s Olympic Dam mine seem to be reluctant and uncertain. The expansion of the Olympic Dam is still a proposal, has
not yet received any environmental assessment approval or been allocated approved budget (BHP Billiton, 2009). Above all this, the uranium grade in the Olympic Dam mine is relatively very low about 2 particles per million (2 ppm), which is just on the edge of giving a net energy deficit (Fleming, personal communication).

**Figure 5.1: Relationship between net energy produced and level of grade ore**

![Graph showing relationship between net energy produced and level of grade ore](source: Storm Van Leeuwen (2008a Part G: p.43))

Kazakhstan is foreseen by the NEA (2008) to be a significant uranium producer in the future due to its rapidly accelerating rate of production since 2004. However, the potential of its uranium mining industry and, the extent to which it will be able to cope with its aspiration in raising its rate of uranium production is unknown and uncertain (Fleming, personal communication; Thomas, personal communication.).
The uranium mining industry in Kazakhstan has recently experienced a fraud, where former officials have illegally shifted the ownership of several uranium mines to other parties (Fleming, personal communication; AFP, 2009 cited in Wise, 2009). This reflects that Kazakhstan’s uranium mining industry is unstable, apart from the country’s domestic and international politics. Consequently, this raises the doubts that the numbers, figures, and statistics published about their increasing production might be inaccurate or incorrect (Fleming, personal communication).

Another essential aspect is that large parts of the country are devoted to uranium mining, in which crucial environmental impacts are likely to occur (Fleming, personal communication).

Simultaneously, Namibia is planning and working to increase its uranium production in response to the projected growth in nuclear power globally, from two mines currently operating, to nine new uranium mines expected to be functioning by 2016 (Wall, personal communication; Ellmies, personal communication). This uranium rush may occur if the economic climate is suitable for new investment (Wall, personal communication.). In other words, it may happen if uranium prices are high enough to encourage investment in Namibia.

There are various challenges, such as water, electricity, infrastructure, health and safety; and environment aspects (Ellmies, personal communication), need to be resolved and provided for in the development of those new uranium mines. Otherwise, there will be a negative impact on the local communities near uranium mines. This is because the current electricity and water networks’ capacities are not sufficient enough to meet any extra demand required for the mining processes (Ellmies, personal communication). This, to some extent, may ensure that the chances of enormous uranium production are limited due to lack of facilities. Currently, a strategic environment assessment, examining the environmental, economic, and social impacts of expanding the uranium mining industry in Namibia, is in progress, and expected to be completed by December 2009 (Ellmies, personal communication).
From the available data regarding the development of new mines in Namibia (Appendix1), it can be noticed that the expected production from most new mines would not produce more than 1000 tU/yr each. Surprisingly, NEA (2008) mentioned that new development of uranium mines are relatively small producers. Namibia’s production may not, therefore, provide the significant contribution needed for the increase in global uranium supply.

The capability of the global uranium mining industry to increase the production rate sufficiently to meet the extra 40% demand and more when the secondary sources become depleted is most likely seen to be a challenge. Moreover, it is may be unlikely to happen and might certainly lead to a shortfall in uranium supplies by 2013 and beyond (Storm Van Leewuen, personal communication; Fleming, personal communication). According to the nuclear industry, the average world production is at 0.73-0.76 of the capacity of the mining companies, implying that, at 100% capacity, uranium supply shortages are likely to occur after 2013 (Storm Van Leeuwen, personal communication).

The main insight of this discussion is that the depletion of uranium resources that yield significant amounts of net energy is the main reason that most likely there will be a scarcity of uranium supplies in the future in meeting the expected increase in demand of nuclear fuel.

The constraints in discovering new high-grade ores may lead to reduced net energy and delay in uranium supply, since it requires more time and effort to extract than that of low-grade uranium. This, in turn, will drive uranium prices to increase very substantially. This is because mining of low grades will be more expensive than conventional costs of mining techniques. Thus, uranium, as a nuclear fuel, is unlikely to ensure security of supplies at affordable prices and combat climate change due to the emissions emitted in the whole process of uranium exploration and exploitation.
5.5 Government advisors

This raises the question why some energy policies are in favour of nuclear power despite the associated risk that most likely to occur and in particular scarcity of uranium supplies. Interviews were intended to be held with key policy-makers and players to answer this question. However, for reasons mentioned in section (3.3.3), it did not happen. This question, though, was asked to the other interviewees. This question seemed to be the hardest in the interviews conducted, in which some had no answer to that question.

The most plausible consensus for this question is that governments tend to consult economists who are certainly persuaded with the economic view that uranium is abundant and replaceable, along with advice given from institutes favouring nuclear power, providing various alternatives for nuclear fuel.

5.6 Advanced nuclear power technologies and alternatives

To counter this, it is argued that Fast Breeder Reactors (FBRs), Generation IV reactors and the use of Thorium are future technologies that will reduce the dependence on uranium, and the risk of its depletion, by reducing its consumption. FBRs are around 50 years' old and they are still facing technical difficulties (Storm Van Leewuen, personal communication). A Generation IV reactor design is similar to that of FBRs (Thomas, personal communication), and still under research and development for use after 2030 (NEA, 2008).

Thorium is not compatible with the existing reactors or reactors under construction, since they require a fundamentally different design when the fuel is Thorium. Significant research and development is needed before Thorium power reactors can be available for commercialisation (Power Technology, 2007; NEA, 2008).
CHAPTER 6
CONCLUSION

This thesis has examined whether or not there will be a nuclear fuel supply risk in the future, in particular 2030 and beyond, if a nuclear revival occurs. In addition, it has analysed the uranium market’s history and the current market conditions to determine the uranium cost implications on economics of nuclear power. This is to determine whether or not uranium, as nuclear fuel, will be available and affordable, to ensure security of uranium supplies.

Uranium is a controversial fuel. Its availability as a nuclear fuel, and market control, are influenced by physical, economic and political outlooks.

The net energy produced from the complete nuclear energy system decreases as level of uranium grades decreases, eliminating the CO$_2$ emissions saved in pursuing nuclear power. The issue is that the extraction of low-grade uranium consumes more time and more energy than extraction of high-grade uranium. Consequently, cost of extraction will increase to cover the increase in mining process expenses, such as extra manpower needed, more extraction facilities, and more electricity needed.

The availability of high-energy, economically extractable uranium to be used as nuclear fuel for meeting future increasing demand depends on the existence of discovered high-grade uranium resources. However, discovered resources of high uranium concentrations are scarce and depleting. The chances of finding new high-grade resources are rare.

Moreover, given the lead time between exploring and discovering new deposits and start of production, it is most likely that the nuclear power plants may run out of nuclear fuel.
Currently, primary uranium production provides around 60% of the total annual nuclear fuel requirement. The remaining 40% of nuclear fuel needed is supplied from secondary sources, most of which are civilian and military stockpiles and inventories, with limited supply of MOX fuel, reprocessed uranium and re-enriched depleted uranium.

These secondary sources are diminishing, since the stockpiles and inventories are running out. There are uncertainties that MOX fuel, reprocessed uranium and re-enriched uranium tails will be able to contribute in the coming decades, due to economic, political, security and technological impacts.

Primary production will have an essential role in meeting the expected 40% shortfall in supplies by 2013, and the expected increase in uranium requirements by 2030. However, it is uncertain that the uranium production capacity will be capable of increasing dramatically to meet the increased demand.

Canada and Australia, which are the world’s largest uranium producers and hold the highest uranium reserves, have a declining rate of production due to technical and processing difficulties arising from natural disasters, such as flooding in their uranium mines. A steady move of mining of lower uranium grade mines as their resource becomes depleted, thereby, requiring more time and effort than previously when they mined high-grade uranium.

Furthermore, although both countries are looking to develop new uranium mining projects, such as Cigar Lake in Canada and the expansion of the Olympic Dam in Australia, both are encountering processing, financial and environmental acceptance difficulties.

Kazakhstan and Namibia are anticipated to become the world major uranium producers, due to recognizable increases in their production in the past few years. However, this increase may not be a regular trend, since these countries do not have sufficient uranium
production capabilities and infrastructure that withstand a huge expansion in their uranium industries.

Supply is affected by various factors, such as mining regulations and policies of countries holding uranium reserves. This, in turn, depends on the political views of the governing party, financial issues, natural disasters, the level of uranium grade, the uranium market, the mining methods used, and technology availability.

With the expected shortfall in primary uranium production, depletion of military and commercial inventories and stockpiles, and extraction of low uranium grades, uranium prices may rise dramatically as a result of undersupply, exceeding the upper limits of affordable raw uranium costs, and eliminating its negligible impact on the economics of nuclear power. The explosion in 2007 of uranium prices may be considered as an initial alarm of what uranium prices might become in the case of inadequate uranium supplies.

This may, though, establish a normal functioning uranium market based on the relationship between production and consumption, and reflect the real uranium prices without the involvement of any secondary factors, as has been happening through the uranium market history.

This thesis concludes that there is likely to be a significant risk of uranium supply constraints in the coming decades, were nuclear capacity to increase by the levels of 509 GWe and 663 GWe for low and high scenarios respectively projected by the NEA and IAEA (2008). This would add a new risk with which to contend in the quest for secure energy supplies that, at the same time, meet the challenges of climate change.

**Recommendations**

- Extraction costs of different uranium grade levels and, in particular, low grades and their impact on economics of nuclear power need to be considered and recognized in the nuclear renaissance debate.
- Insight and understanding in distinguishing between the availability of uranium as an element and the availability of energetically recoverable uranium as an energy resource needs to be provided in the debate of uranium adequacy.

- The risk of uranium supplies scarcity needs to be dispersed and to be given a higher priority in the nuclear power debate; and in the nuclear power policies agendas.

- Uranium is becoming an essential energy fuel for providing sustained energy services for current and coming generations. Full transparency of facts, evidence and figures regarding estimates of uranium resources, production capacity and its opposing constraints, size of civil and military inventories and stockpiles and their rate of consumption, and uranium market need to be provided from energy utilities, uranium mining companies, and governments, for fair assessment and knowledge of uranium supplies and its impacts for ensuring energy security.

- Nuclear power is unsustainable, and uranium is a finite resource and will run out.
  
  Time, money, and effort spent on nuclear power development could saved to be spent in other sustainable, clean, and safe technologies, such as renewable energy (where the sun, wind and waves will never run out), energy efficiency and demand reduction

- More research on examining the environmental, social and economic impacts of uranium mining on local communities living nearby the uranium mines being exploited and, particularly, in developing countries, is needed.
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Wall, F. (personal communications). Face – Face interview conducted on 7th July 2009 in Cornwall.


FURTHER READINGS


APPENDIX 1

RECENT MINE OPENINGS

2005
Kazakhstan (Kendala JSC- Central Mynkuduk, 2 000 tU/year in 2010)

2006
Iran (Bandar Abbas, 21 tU/year)
Namibia (Langer Heinrich, 1 000 tU/year)

New mines planned (date indicates estimated start of production)

2007
China (Qinlong, 100 tU/year)
Kazakhstan (Appak LLP-West Mynkuduk, 1 000 tU/year in 2010)
Kazakhstan (Karatau LLP- Budenovskoye, 1 000 tU/year in 2009)
South Africa (Uranium One – Dominium & Rietkuil, 1 460 tU/year in 2010)

2008
Australia (Honeymoon, 340 tU/year)
Kazakhstan (Semizbai-U LLP – Semizbai, 500 tU/year)
Kazakhstan (Kyzylkum LLP – Kharasan-1, 3 000 tU/year in 2010)
Kazakhstan (Southern Inkai, 1 000 tU/year)
Kazakhstan (Irkol, 750 tU/year)
Kazakhstan (Baiken-U LLP– Kharasan, 2 000 tU/year in 2014)
Kazakhstan (Akbastau JV JSC – Budenovskoye, 3 000 tU/year)
Namibia (Trekkopje, 1 600 tU/year)
Russia (Khiagda, 1 000 tU/year, 2 000 tU in 2015)

2009
Iran (Saghand, 50 tU/year)
Malawi (Kayelekera, 1 270 tU/year)
Namibia (Valencia, 1 000 tU/year)

2010
Canada (Midwest, 2 300 tU/year)
<table>
<thead>
<tr>
<th>Year</th>
<th>Country</th>
<th>Location/Region</th>
<th>Uranium Production (tU/year)</th>
</tr>
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<tbody>
<tr>
<td>2011</td>
<td>India</td>
<td>Tummalapalle</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>Russia</td>
<td>Gornoe</td>
<td>600</td>
</tr>
<tr>
<td>2011</td>
<td>Brazil</td>
<td>Itataia</td>
<td>680</td>
</tr>
<tr>
<td></td>
<td>Canada</td>
<td>Cigar Lake</td>
<td>6900</td>
</tr>
<tr>
<td></td>
<td>India</td>
<td>Mohuldih</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Niger</td>
<td>Imouraren</td>
<td>5000</td>
</tr>
<tr>
<td></td>
<td>Niger</td>
<td>Azelik</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>Russia</td>
<td>Olov</td>
<td>600</td>
</tr>
<tr>
<td>2012</td>
<td>India</td>
<td>Lambapur-Peddagattu</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>India</td>
<td>Killeng-Pyndengsohiong</td>
<td>340</td>
</tr>
<tr>
<td></td>
<td>Russia</td>
<td>Elkon</td>
<td>5000</td>
</tr>
<tr>
<td>2015</td>
<td>Ukraine</td>
<td>Severinskoye</td>
<td>1200</td>
</tr>
<tr>
<td>2010-2030</td>
<td>Kazakhstan</td>
<td>Central Moinkum</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>Kazakhstan</td>
<td>Zhalpak</td>
<td>1000</td>
</tr>
</tbody>
</table>

Source: (NEA & IAEA, 2008: p. 49)
## APPENDIX 2

### PLANNED MINE RE-OPENINGS OR EXPANSION OF EXISTING FACILITIES

**2007**
- China (Expansion of Fuzhou to 200 tU).
- India (Production at Banduhurang mine in sandstone).
- India (Production centre at Bagjata mine in vein).

**2008**
- Australia (Ranger: Construction of a laterite treatment plant to produce 340 tU/year, over seven years).

**2009**
- Niger (Expansion of Somair plant production capability, and construction of a heap leaching unit – 700 tU/year).

**2010**
- Canada (McArthur River and Key Lake expansion to produce 8 800 tU/year).
- Kazakhstan (Southern Zarechnoye, 1 000 tU/year).
- Brazil (Caetité expansion to 340 tU/year)

Source: (NEA & IAEA, 2008: P. 47)
## APPENDIX 3

### ABBREVIATIONS, ACRONYMS, AND UNITS

#### Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
<th>Abbreviation</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>CANDU</td>
<td>Canadian Deuterium Uranium</td>
<td>ESA</td>
<td>Euratom Supply Agency</td>
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<tr>
<td>EU</td>
<td>European Union</td>
<td>HEU</td>
<td>Highly Enriched Uranium</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
<td>IR</td>
<td>Inferred Resources</td>
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<tr>
<td>ISL</td>
<td>In situ Leaching</td>
<td>LWRs</td>
<td>Light Water Reactors</td>
</tr>
<tr>
<td>NEA</td>
<td>Nuclear Energy Agency</td>
<td>NEA &amp; IAEA</td>
<td>Red Book 2008</td>
</tr>
<tr>
<td>NGOs</td>
<td>Non Governmental organisations</td>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
</tr>
<tr>
<td>WNA</td>
<td>World Nuclear Association</td>
<td>Pu</td>
<td>Plutonium</td>
</tr>
<tr>
<td>RAR</td>
<td>Reasonable Assured Resources</td>
<td>U</td>
<td>Uranium</td>
</tr>
<tr>
<td>U3O8</td>
<td>Uranium Oxide</td>
<td>UF6</td>
<td>Uranium Hexafluoride</td>
</tr>
<tr>
<td>$</td>
<td>US Dollars</td>
<td>GWe</td>
<td>Gigawatt electric</td>
</tr>
<tr>
<td>GWe/yr</td>
<td>Gigawatt electric per year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>kg</td>
<td>Kilogram</td>
<td>KgU</td>
<td>Kilogram Uranium</td>
</tr>
<tr>
<td>MTSWU</td>
<td>Metric Tons of Separative Work Units</td>
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<td></td>
</tr>
<tr>
<td>MW/ MWe</td>
<td>Megawatt (electric)</td>
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<tr>
<td>Symbol</td>
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<tr>
<td>ppm</td>
<td>Particles Per Million</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>Tonne</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t/yr</td>
<td>Tonne per year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tU</td>
<td>Tonne of Uranium metal</td>
<td></td>
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<tr>
<td>tU/yr</td>
<td>Tonne of Uranium metal per year</td>
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