Uranium for energy resources

Jan Willem Storm van Leeuwen
Independent consultant

member of the Nuclear Consulting Group

September 2019
storm@ceedata.nl

Note
In this document the references are coded by Q-numbers (e.g. Q6). Each reference has a unique number in this coding system, which is consistently used throughout all publications by the author. In the list at the back of the document the references are sorted by Q-number. The resulting sequence is not necessarily the same order in which the references appear in the text.

Contents

1 Uranium as commodity
- The element uranium
- Composition of the continental crust
- Distribution of metals in the Earth's crust
- Uranium occurrences
- No uranium ores in the ocean's floor
- Extraction of uranium from its host rock

2 Mineralogical barrier

3 Uranium distribution in the Earth's crust
- Uranium deposits
- Log-normal or bimodal distributions?
- Crustal distribution of uranium according to Deffreyes & MacGregor
- Empirical evidence
- Prospects of new discoveries

4 Thermodynamic quality of uranium resources
- Energy system
- Themodynamic quality
- Methodology
- Energy cliff
- Net energy potential of uranium resources

5 Uranium resources - the industrial view
- Uranium ore
- Economic viewpoint
- Supply curves
- Just a mineral or an energy source?
- Abundancy of uranium
- Ore types
- Mining costs and ore grade

6 Recoverable uranium resources
- Resource terminology
- Cost categories
- World known uranium resources
- Undiscovered resources

7 Long-term perspective
- Supply potential
- Other uranium resources
- Technical promises versus realism

References

TABLES

Table 1 Nine most abundant elements in the continental crust
Table 2 Eight second most abundant elements in the Earth’s crust
Table 3 Abundancy of uranium in various geologic reservoirs
Table 4 World known recoverable uranium resources
Table 5 Uranium resources and resource/production ratios.

FIGURES

Figure 1 Mineralogical barrier and specific extraction energy
Figure 2 Hypothetical log-normal distribution of uranium in the Earth’s crust
Figure 3 Hypothetical bimodal distribution of chromium in the Earth’s crust
Figure 4 Ditribution of uranium in the major geologic reservoirs
Figure 5 World known uranium resources, grade distribution
Figure 6 Energy cliff and the world known uranium resources
Figure 7 Economic model of uranium resources, according to WNA
Figure 8 Relationship total amount of uranium and ore grade
Figure 9 Simple supply curve of uranium: amount vs cost
Figure 10 Hypothetical complex supply curve of uranium
Figure 11 Ore grade vs production costs (1982)
Figure 12 Approximate correlation of terms in major resources classification systems

1 Uranium as commodity

The element uranium

Uranium in pure form is a white, radioactive metallic element, of density 19 g/cm^3. Naturally occuring uranium contains three isotopes, in the proportions:

uranium-234 0.0055%
uranium-235 0.720%
uranium-238 99.274%.

Only uranium-235 nuclei are fissile, the other uranium nuclei are non-fissile. So, not more than 0.7% of natural uranium is available for generation of nuclear power in the current generation of power reactors.

Uranium is a chemically reactive metal, and therefore never found in nature as native metal, like the noble metals. In the Earth's crust uranium is present in the form of many different chemical compounds, embedded in various types of host rocks. To make nuclear energy generation possible, the uranium has to be extracted from its host rock and converted into nuclear fuel elements. The nuclear fuel elements are placed into a nuclear reactor. The fission energy is liberated as heat, which is converted into electricity via a steam cycle.

The raw energy resource of nuclear power is the uranium-bearing rock, from which the uranium is extracted. In this respect uranium is different from the other mineral energy resources: the fossil fuels oil, coal and gas. Fossil fuels are present in the ground as carbon-hydrogen compounds, ready to burn at any place in any heating system. The only thing man has to do is to bring a fuel to the surface and transport it to the consumer.

The uranium-bearing minerals , however, are finely dispersed in other types of rocks, often at low concentrations. After bringing the ore to the surface, comparable to the mining of coal, the uranium minerals have to be separated from the rocks, before purification of the uranium compound and conversion of it into nuclear fuel can start.

To get some insight into the complex issue of uranium resources as energy source and the outlook for the future, we first turn to some basic geological and mineralogical aspects of metal ores.

Composition of the continental crust

The average content of any chemical element on Earth, called the crustal abundance of that element is expressed as percentage by weight. The 88 elements found on Earth, except the noble gases, combine to form minerals: solid crystalline chemical compounds or elementary substances. For example quartz is a compound of silicon and oxygen, diamond is pure carbon. Rocks are natural aggegations of of one ore more minerals, e.g. granite and limestone.

Nine elements make up 99.0% of the mass of the Earth's crust (see Table 1), the remaining 79 elements total only 1.0% of the crust and are therefore present in essentially trace amounts. Oxygen and silicon, the two most abundant elements, form complex silicates. Earth's crust is 99.0% by weight a mass of oxide and silicate minerals in compounds with the other seven elements from Table 1.

The most important of the minor mineral families, based on the next two most abundant elements carbon and sulphur, are the carbonates, sulphides and sulphates. The most common carbonate, sulphide and sulphate minerals are all formed with the six most common cations of Table 1. The general chemistry of the

crust is therefore largely the chemistry of silicate minerals with a small addition of a few oxide minerals, the carbonates of calcium, magnesium and iron, the sulphides of iron and the sulfates of calcium.
Tables 1 and 2 show that the remaining 74 elements make up less than 0.7% of the mass of the crust and may be considered scarce.

Table 1

The nine most abundant elements in the continental crust, source: [Skinner 1979] Q322. The concentrations vary with location. Other sources may cite slightly different values.

element		crustal abundance mass-% (g/100 g)
O	oxygen	45.2
Si	silicon	27.2
Al	aluminium	8.0
Fe	iron	5.8
Ca	calcium	5.1
Mg	magnesium	2.8
Na	sodium	2.3
K	potassium	1.07
Ti	titanium	0.9
	sum	99.0

Table 2

The eight second most abundant elements in the Earth's crust. Source: Handbook of Chemistry and Physics. The concentrations vary with location. Other sources may cite different values.

element		crustal abundance mass-% (g/100 g)
P	phosphorus	0.105
Mn	manganese	0.095
Ba	barium	0.0425
S	sulphur	0.035
C	carbon	0.0200
Zr	zirconium	0.0165
Cl	chlorine	0.015
V	vanadium	0.012
	sum	0.34

Distribution of metals in the Earth's crust

Minerals are crystalline ionic compounds consisting of anions (negatively charged ions) and cations (positively charged ions). Oxygen forms oxide anions and complex silicate anions with silicon. The metals in the crust are present as cations. When two metal ions have similar charge one can substitute for the other in a mineral without producing a change in the geometry of the crystal structure (ionic lattice) and therefore without producing a new mineral. If the ionic radii differ less than 15%, complete substitution is usually possible. When the differences in ionic radii are greater than 15%, some substitution is still possible, but there are definite limits beyond which the addition of much smaller or much larger metal ions will cause mineral structures to change or, more commonly, to form a separate mineral. In this new mineral the substituting element becomes the major charge-balancing cation [Skinner 1979] Q322.

Because most elements occur in such tiny amounts in the contintal crust they can readily be accomodated by substitutions in common oxide and silicate minerals without the saturation point being reached and therefore without separate minerals being formed. In this way the scarce elements form solid solutions in the common minerals. The only way separate minerals of the scarce elements can form is for some geologic process to cause a local enrichment of one of the scarce elements so that the saturation limits are exceeded.

The major rock-forming processes are:
- weathering and sedimentation to form sedimentary rocks,
- melting and fractional crystallization to form igneous rocks,
- new mineral growth by heat and pressure to form metamorphic rocks.

The processes rarely cause sufficiently great enrichments of the scarce elements to exceed the saturation imits, so separate minerals of the scarce elements are rare. Most of the sarce elements never form separate minerals.

No definite rules can be drawn as to the concentration that any given element must reach before a separate mineral can form. Most elements will start to form separate minerals when a concentration of about 0,1% is reached. Uranium is one of the few elements having a combination of ionic radius and ionic charge that makes substitution possibilities more limited than of other elements, therefore uranium forms separate minerals at concentrations much lower than 0.1%.

Metals can be roughly divided into three geochemical groups on the basis of the way they are found in minerals ccording to Skinner.

Group 1

Group 1 consists of silicon and the metals iron, aluminium, titanium and magnesium, that have crustal abundances inexcess of 0.1%. These elements form common minerals in a great many kinds of rocks.

Group 2

The elements of Group 2 have crustal abundances between 0.1 and 0.01%. In this abundance range many rock-forming processes produce the concentration necessary for separate minerals to form. This group, including barium, phosphorus, manganese, vanadium and zirconium, is therefore also present as minerals in many common rocks.

Group 3

This group contains all metals with crustal abundance lower than 0.01%. These metals rarely forms separate minerals and, when formed, those minerals are not found in any of the common rocks. They are found, instead, in mineral deposits formed by special and unusual chemical circumstances. The mass of the mineral deposits of the metals of Group 3 is minute compared to the mass of common rocks. This group are the geochemically scarce metals.

With a crustal abundancy of about 0.00027% uranium obviously belongs to group 3.

Uranium occurrences

Geologic resources are distributed unevenly over the surface of the globe and they are concentrated in the outermost part of the earth's continental crust. Mechanisms that concentrate uranium operate most effectively on or near the earth's surface. Ore bodies tend to get poorer and harder to mine downward [Cook 1976] Q344. This phenomenon is, for instance, observable in the current practice at Ranger and Olympic Dam in Australia.

Large mineral deposits are extremely rare. Most mineral commodities show a marked tendency to occur in clusters, known as mineral provinces, and uranium is no exception. The largest uranium resources of the world are located in a few regions: Australia, Brazil, Canada, South Africa + Namibia, Niger and Kazakhstan. Of these regions Australia has by far the largest known deposits and Kazakstan the second largest; Canada stands on a good third place.

The mass of any geochemically scarce metal in the Earth's crust can be calculated, for its crustal abundance is known, but it is difficult to estimate the fraction of a metal trapped by atomic substitution and the fraction present in separate ore minerals.
Empirical geochemical methods suggest that the amount of a scarce metal present in ore minerals falls somewhere in the range 0.01-0.001% of the mass of that metal in the crust [Skinner 1979] Q322.

If we consider the upper 2.5 km of the continental crust, with a mass of 10^{18} Mg, as resource base, the total amount of uranium minerals in that part of the crust would contain 27-270 Tg (million Mg) uranium. [Uytenbogaardt 1980] Q319 cites a value of 27 Tg.

Knowing how much uranium occurs in separate minerals is only part of the problem. The remainder of the problem concerns the way the mineral grains are distributed in the crust – that is, the grade and size distribution of the ores.

The formation of an ore deposit requires a sequence, favourable combination and repetition of transport processes. The physical/chemical characteristics and crustal abundance of a given element, in contrast to those of all other elements affected by such processes, determine the concentration efficiency of a given transport process for that element.
It's plausible that the same processes which are responsible for the formation of ore deposits with equal ease destroy formerly existing mineral concentrations. The current distribution of element concentrations in the continental crust is the momentary result of a turbulent movement of mineral matter through this environment.

A great many mineral deposits, including uranium deposits, are formed through processes in circulating aqueous solutions, which are prevalent in the top 2-5 km of the crust. This implies that the frequency of deposits will decrease with depth. The formation of uranium minerals require a selective transport mechanism, by which uranium is transported from a region at average concentration, which becomes depleted in uranium, to another region, which becomes enriched in uranium. Beyond a given saturation limit, crystallization of separate uranium minerals is possible.

Uranium as present in common rocks (in solid solution or separate minerals) usually is tetravalent, U(IV), meaning the ions have a charge of 4+. U(IV) compounds are insoluble in water. Oxidation of uranium to the hexavalent state U(VI), e.g. by oxygen from the air, makes it soluble. Uranium(VI) compounds can be transported by a water circulation. In a reducing environment, e.g. an anaerobic organic sediment, the uranium ions are reduced to the tetravalent state again and become insoluble in water. Under favourable conditions a separate uranium mineral may crystallize.

No uranium ores on the ocean's floor

Mineral deposits of scarce metals in the deep-sea floor are highly unlikely, according to [Skinner 1979] Q322. Formation of most metalic mineral deposits requires a localized energy source to drive circulation systems that deposit the ore minerals. The oceanic crust encounters a heat source at the spreading edge of a plate, but thereafter the oceanic crust seems to remain quiet and unaffected by mineralizing processes, until it reaches a subduction zone. Much of the continental crust, by contrast, has been subjected to many periods of mechanical and thermal activity and has therefore had many chances for ore deposits to form.

Extraction of uranium from its host rock

A typical uranium ore consists of a large mass of valueless silicate minerals mixed with a small quantity of a uranium mineral.
The classic extraction methods, on which the extraction yield curve used in this study has been based (see report, usually start with beneficiation: sorting out the uranium mineral grains from the bulk of the ground host rock as much as possible by physical means (e.g. flotation). So only a part of the uranium-bearing rock has to be actually dissolved in an appropiate solvent (e.g. dilute sulphuric acid), without attacking the silicate minerals, which compose the bulk of the ore mass. The resulting solution ('pregnant liquor') is processed with chemical extraction techniques.
Beyond the mineralogical barrier the whole rock has to be dissolved to extract the uranium ions, which are present in the host rock in a so-called solid solution, without forming separate uranium mineral grains. This geochemical phenomenon causes the specific energy consumption of the extraction to jump with a factor of 10 or more. Report m26 *Uranium mining + milling* addresses this issue in detail..

Technically it is possible to extract uranium from rocks with a exceedingly low uranium content, e.g granites, or from seawater. The question is not: is it technically possible? but: would it be useful? How much energy will the extraction consume? The only civil use of uranium is as an energy resource, to provide the society with freely usable energy. This is quite unlike other metals (e.g. copper), which have no function as an energy source. If the extraction of 1 kg uranium from its resource will consume as much eneregy as can be generated from that 1 kg uranium, extraction is not useful anymore.

Extraction uranium from a solid solution implies dissolution of the complete matrix of the uranium-bearing rock. Especially silicates, about 99% of the Earth's crust, are very resistant to chemical attack. Only with extremely energy-consuming techniques, for instance electrolysis of molten rock, the element uranium could be separated from its silicate matrix. The specific energy requirements of the extraction of 1 kg uranium from silicate rock will be at least a factor 10 higher than from a conventional ore (rock containing a separate uranium mineral) at the same average grade.

2 Mineralogical barrier

Mineralization limit

The earth's crust consists 99.5% by weight of silicate and oxide minerals in which aluminium, iron calcium, magnesium, sodium, potassium and titanium are the cations (ions with a positive charge). The remaining 79 elements total only about 0.5% of the crust and are therefore present in essentially trace amounts. The most important of the minor mineral families are the carbonates, sulphides and sulphates.

Because most chemical elements occur in such tiny amounts in the crust, their ions can readily be accommodated in common oxide and silicate minerals by substitution of more abundant ions. The only way minerals of the scarce elements can form is for some unusual, and therefore rare, geological process to cause a local enrichment of element, in case uranium. At a certain enrichment level, a substitution limit is reached, set by the geochemical properties of uranium. Above the substitution limit a separate uranium mineral forms, in which uranium becomes the major cation. The uranium mineral, for example pitchblende UO_2, is found as small grains between the other mineral crystals in the host rock.
The grade boundary between rocks with and rocks without separate X minerals is called the mineralogical barrier by [Skinner 1979] Q322. Any scarce metal has is own mineralogical barrier, according to Skinner. Copper for instance has its barrier at a grade of about 0.1% by weight of copper.

The uranium mineralization limit has a lower value than copper, due to the special geochemical properties of the element uranium. Uranium is usually present as U^{4+} cations. The uranium mineral pitchblende or uraninite UO_2, for example, is found as small grains between the common silicate crystals in the host rock.
Due to its large ionic valence (4+) combined with its large ionic radius (0.089 nm) uranium ions cannot easily substitute other cations in ionic crystal lattices, for only a small number of similar cations are existing, one of them being tetravalent zirconium Zr^{4+}.
According to [Deffeyes & MacGregor 1980] Q281, uranium in granite is usually concentrated in a few of the less abundant minerals rather than being evenly scattered throughout the major minerals. One of that 'less abundant' minerals is zircon $ZrSiO_4$, one of the most refractory minerals known.

A typical uranium ore consists of a large mass of valueless silicate minerals mixed with a small quantity of a uranium mineral. The extraction of uranium from the mix implies dissolving the small grains of the uranium mineral in an appropiate solvent (e.g. dilute sulphuric acid), without attacking the silicate minerals, which compose the bulk of the ore mass.

In rocks with a uranium content below the substitution limit, no uranium mineral grains are present. The uranium is dispersed, instead, in the lattices of the bulk minerals (usually silicates) of the host rock, replacing other cations. This condition is called a solid solution of uranium. Examples of a solid solution of uranium are phosphate rocks and granites. Solid solutions are not amenable to selective physical and chemical extraction. To recover the uranium from such a rock type, the complete mass of minerals of the host rock has to be brought into solution.

Mineralogical barrier

The grade boundary between rocks with and rocks without separate metal minerals is called the mineralogical barrier by [Skinner 1979] Q322 and [Skinner 2001] Q388. Any scarce metal has is own mineralogical barrier. Copper for instance has its barrier at a grade of about 0.1% by weight of copper. The uranium mineralization limit has a lower value than copper, due to the special geochemical properties of the element uranium

and depends on the chemical composition of the host rock. This study found no numerical values of the mineralogical barrier of uranium.
For mining operations the mineralogical barrier has profound consequences, for the inputs of energy and materials required for the extraction jump by a factor 10 or more beyond the barrier.

The mineralogical barrier is seldom mentioned in reports regarding metal resources. There is a report from a gold mining company, saying that the company is working at comfortably higher grades than the mineralogical barrier of gold [DRDGold 2005] Q334, without mentioning the value of it.
This study found no publication mentioning the possible existence of a mineralogical barrier of uranium.

Beyond the mineralization limit

Technically it is possible to extract uranium from rock with very low uranium content, for instance granites, shales and phosphate rock, but at the expense of high consumption rates of materials and energy.
In rocks with grades beyond the mineralization limit uranium is present in solid solution (see section above on the mineralogical barrier). Consequently the whole rock mass has to be dissolved to liberate the uranium ions. Due to the very low uranium concentration and high concentrations of many other species in the solution, exceedingly selective extraction techniques are necessary. The high selectivity and the large volumes of solutions to be treated imply a high specific energy consumption.

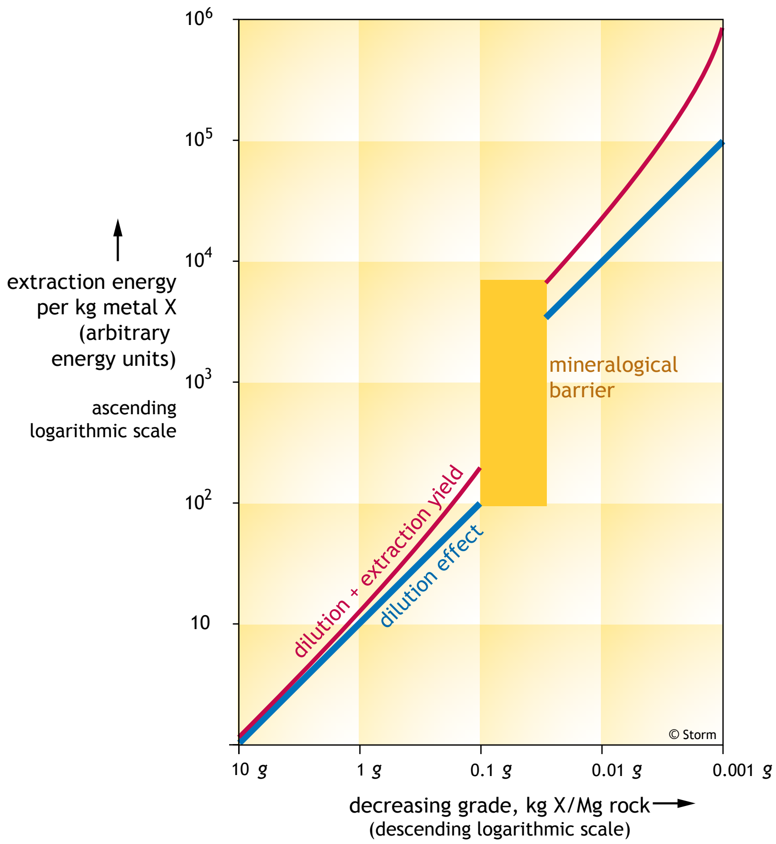

Figure 1
Mineralogical barrier and specific extraction energy of a scarce metal X from the earth's crust. Both scales are logarithmic, the vertical scale has arbitrary energy units per kg recovered metal, the horzontal scale grade of metal X as a multitude of an arbitrary grade *g*.

3 Uranium distribution in the Earth's crust

Uranium deposits

Deposits of uranium minerals (and of other scarce elements) in the earth's crust are formed only when several improbable circumstances occur together: there must be a source of the element, enough water to transport it, suitable subsurface conduits, suitable chemical conditions (oxidizing at one site, reducing at another site), complexing agents to carry the element in solution and other agents to finally precipitate the mineral.
It should be noted that the same mechanisms that form uranium mineral deposits, also are able to destroy earlier formed deposits.
The probability that an ore deposit will be formed and will survive until today at a given site is determined by multiplying the probabilities of each esential ingredient being present.

No uranium minerals can be formed on the sea floor, due to the absence of suitable chemical conditions. However, dissolved uranium ions are present in seawater in very low concentration.

Log-normal or bimodal distribution?

The probability that an ore deposit will be formed and will survive until today at a given site is determined by multiplying the probabilities of each essential ingredient being present. When probabilities add, the central-limit theorem of statistics holds that the final distribution approaches the bell-shaped normal distribution. Since the multiplication of probabilities corresponds to adding on a logarithmic scale, it is not surprising to see the familiar bell-shaped curve appear when elemental abundances are plotted on a logarithmic scale.
Figure 1 illustrates the hypothetical log-normal distribution of uranium in the earth's crust, if above statistical reasoning were to apply to uranium. The peak of the curve is at the average crustal abundance of 2.8 ppm.

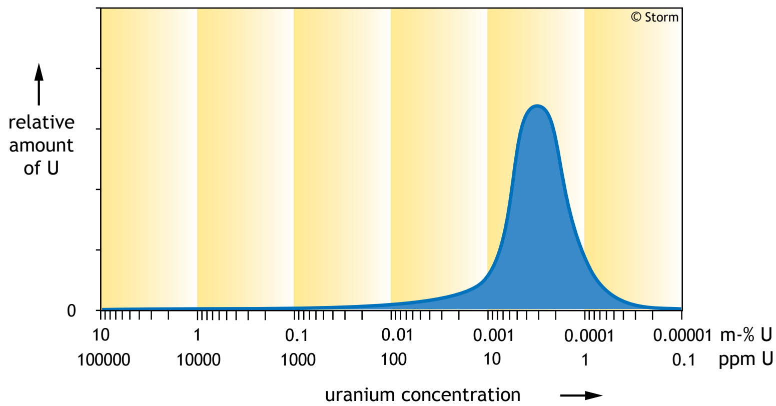

Figure 2
Hypothetical log-normal distribution of uranium in the earth's crust, if such a distribution were to apply to uranium. Source: [Deffeyes & MacGregor 1980] Q281. Note that the horizontal axis has a logarithmic scale (decreasing uranium concentration) and the vertical axis a linear scale. The area under the curve represents the total amount of uranium in the earth's continental crust. The peak is at the average crustal abundance of 2.8 ppm.

An alternative model of the overall crustal distributions of the trace elements has been put forward by Brian J. Skinner. In Skinner's model the crustal distributions of the trace elements follow a bimodal curve, with one peak for the ore deposits and a second peak for the common rocks [Deffeyes & MacGregor 1980] Q281. Skinner proposed this theory for lead, but it could apply to other trace metals as well. Chromium, for example, may have a bimodal distribution (see Figure 3).

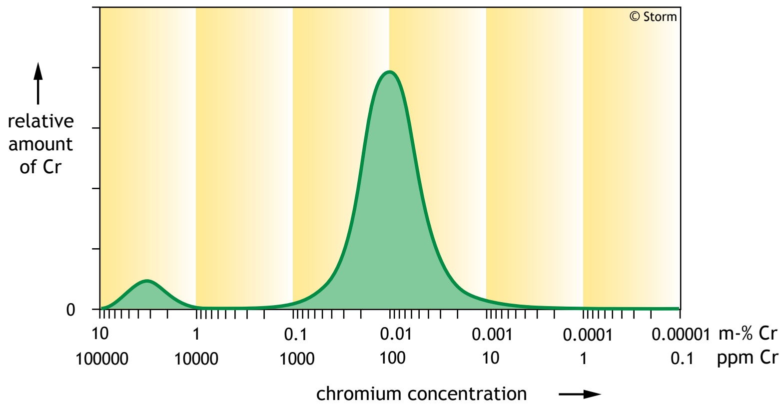

Figure 3

Chromium may have a bimodal distribution in the earth's crust, with one peak for the ore deposits and one peak for common rocks. Source: [Deffeyes & MacGregor 1980] Q281. This distribution would correspond with the theory of Brian Skinner. This distribution would cause a supply curve like the one in Figure 10.

Crustal distribution of uranium according to Deffeyes & MacGregor

Within the nuclear world the opnion with regard to the crustal distribution of uranium appears to be based on the authoritative study of [Deffeyes & MacGregor 1980] Q281. The study [MIT 2003-2009] Q280 based its view on the prospects of the future uranium supply on the Deffeyes & MacGregor (D&M) study and no other studies on this topic are refered to in the nuclear field.

Inventarising the known uranium occurences in the world, D&M postulated a global abundance distribution among the major geological reservoirs of uranium as presented in Figure 4. The rich ore deposits in the Athabasca Basin in Canada, with grades higher than 3%, were not included in the publication of D&M. These deposits have been added by us (blue bars), although they are measured up to depths of 500-600 meters, whereas the remainder of the diagram refers to the earth's crust without an indication of depth. The continental crust is over 30 km thick. The authors D&M emphasize that the distribution of uranium in the earth's crust is not known, so their diagram is a rough estimate.
According to Deffeyes & MacGregor the diagram of Figure 4 appears to support the hypothesis of a single log-normal distribution. However, it is not possible to determine the distribution of uranium deposits directly. Uranium exhibits a complex range of geochemical behaviour and a wide variety of different kinds of economic deposit. Other possible distributions would be a bimodal one, with two peaks, or a multimodal one, with more peaks in the distribution curve. As D&M put it:

> "There is no underlying theoretical theory requiring that the abundance in the earth's crust of trace elements such as uranium should follow a log-normal distribution."

and:

> "... no rigorous statistical basis exists for expecting a log-normal distribution."

D&M think it plausible that the hypothesis of a log-normal distribution of uranium may be correct, based on an analysis of the uranium production of US mines. Their analysis does not encompass the world uranium production. More complex distributions are not refuted nor disproved.

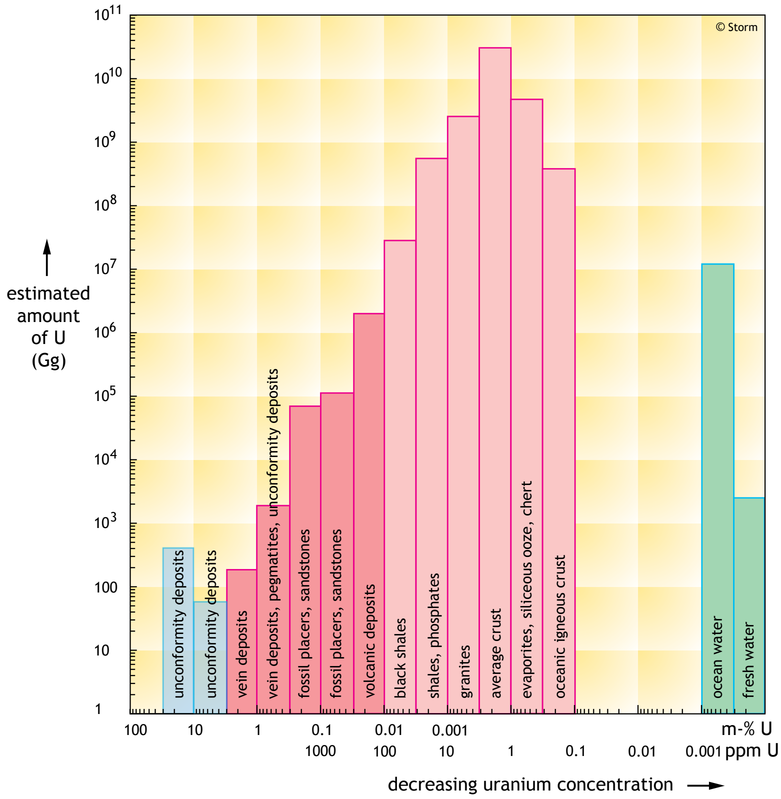

Figure 4

Distribution of uranium in the major geological reservoirs, according to [Deffeyes & MacGregor 1980] Q281. Note that both the horizontal and the vertical axes have a logarithmic scale. The bars representing estimated total amount of uranium in the various categories of ore deposits define a log-normal global-abundance curve, which in this instance takes the form of a parabola. The ascending slope of the parabola is roughly 2.5 to 1, which corresponds to a 300-fold increase in the estimated amount of recoverable uranium for every tenfold decrease in the ore grade.

The darker shaded bars on the left represent the reservoirs from which uranium is extracted in the current practice, down to the grade interval of 0.03 - 0.01% uranium. The rich deposits in Canada, with grades of more than 3% uranium were absent in the original publication of Deffeyes & MacGregor, and have been added by the author of this study (the two light blue bars at the far left).

The diagram of Deffeyes & MacGregor gives no clue on the mineralization of uranium, the presence of ores and the recoverability of the uranium from the various geological reservoirs.

No uranium minerals can be formed on the sea floor, due to the absence of suitable chemical conditions. However, dissolved uranium ions are present in seawater in very low concentration.

Empirical evidence

The distribution of uranium according to Deffeyes & MacGregor, though probably the best information we have today, still is a rough estimate. The authors emphasize that there is no theoretical or statistical base that would prove the proposed log-normal distribution to be correct.

Besides, the distribution of uranium according to Deffeyes & MacGregor refers to the earth's crust at large. Obviously only a fraction of the continental crust is technically accessible for uranium mining. Today's uranium mines are considerably less deep than 1 km, typically less than 500-600 m. BHPBilliton, the owner of by far the largest known uranium deposit of the world, Olympic Dam in Australia, is considering to expand the underground mine to an open pit mine with a maximum depth of 1200 m [ODX 2007] Q354. At that depth Olympic Dam would become the deepest reported uranium mine.

The only empirical evidence on the crustal uranium distribution is the ore grade distribution of the known uranium resources, illustrated by Figure 5.

According to the [Red Book 2008] Q90 the known recoverable uranium resources at a production cost of 130 USD/kg U or less were listed at 5.47 Tg (1 teragram = 1 million metric tonnes), per 1 January 2007. In de open literature no physical data could be found of some 0.9 Tg of these resources. Judging by their locations, the resources of undisclosed grade and mineralogy are likely very low-grade deposits and their ore grade range is estimated in this study by comparison with adjacent resources.

Per 1 January 2013 RAR + Inferred resources were estimated at 5.90 Tg at a production cost of up to 130 USD/kg U [Red Book 2014] Q90, slightly more than in 2007. The ore grade distribution in 2013 does not differ significantly from the distribution based on the 2007 figures, because the additional resources are chiefly the result of reclassification of resources already known.

The Red Book tables are a compilation of submissions from the uranium producing countries themselves and political arguments may affect the figures. The tables are not based on geologic surveys performed by an independent scientific institute.

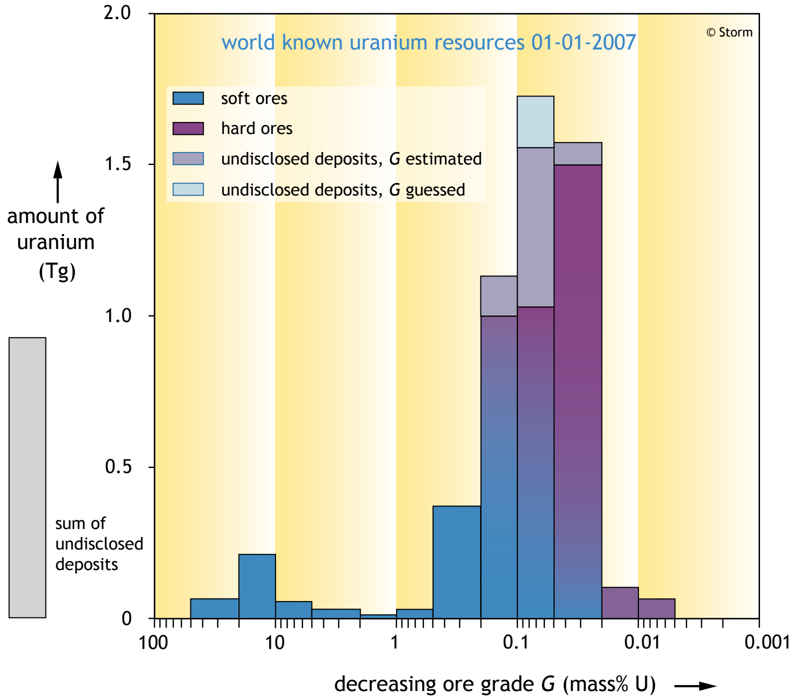

Figure 5

World known recoverable uranium resources. The total amount of uranium represented by this diagram is 5.469 Tg (1 teragram = 1 million metric tonnes), corresponding with the total resources (RAR + Inferred cost category up to 130 USD/kg U) per 01-01-2007 as stated by the IAEA-OECD/NEA [Red Book 2008] Q90. The ore grade distribution is not given by the Red Book and comes from a number of other sources: [NAC 1982] Q53, [WNA-75 2010] Q85, [UIC-34 2005] Q86, [WNA 2005] Q87, [WNA-48 2006] Q210, [UIC-emine 2005] Q211, [WNA49 2011] Q212, [UIC-pmine 2005] Q213, [WNA-27 2014] Q314, [WISE-U 2008] Q324, [Areva 2007] Q369, [Forsys 2007] Q367, [Turpis 2008a+b] Q370, [IAEA 1996] Q371. The ore grade distribution in 2013 does not differ significantly from the distribution based on the 2007 figures, because the additional resources are chiefly the result of reclassification of resources already known.

Note that the horizontal axis has a logarithmic scale, with decreasing ore grade, and the vertical one a linear scale. The quantity of uranium present in a resource at a given grade interval is represented by the height, not the area of a bar. The width of a bar represents the ore grade interval. For explanation of the grey bars see text.

At lower grades uranium ores tend to be harder to mine and to process, due to more refractory uranium minerals and harder host rocks. Soft ores (blue shaded bars) are the easier to process than hard ores (purple).

.

Summarized, the ore grade of roughly 4.5 Tg of the known resources are disclosed, and these resources are the basis of the ore grade distribution of the known world uranium resources in Figure 5. The resources of which the ore grades are not published in de open literature are in Figure 5 represented by grey bars.

The observed uranium ore grade distribution shows a bimodal pattern. A striking feature is the virtual absence of uranium ores with grades in the range of 1-2% U. If uranium were to exhibit a log-normal distribution, like most other metals, one could expect significant uranium deposits to be found with grades in the range of,say, 5-0.5% U. Up until 2014 no such evidence has been reported.

The discrepancy between the geological estimate and ‘known recoverable resources’ increases as the ore grade goes down. Moving toward lower uranium grades the economic incentive to map uranium deposits goes down because the high-grade deposits will not mined out for a decade, or more. There is therefore little point in spending money in exploring low-grade deposits now.

Little uranium deposits are labeled ‘ores’ at grades below 0.02% U (200 ppm U), as Figure 4 shows, in spite of the huge amounts of uranium which would be present in deposits at this grades, according to the study of Deffeyes & MacGregor. Likely this obsrvation is not a geologic feature, but a consequence of the economic definition of ‘recoverable resource’. [Brinck 1975] Q55 mentions a lower limit of uranium ores at 0.020%.

Prospects of new discoveries

There is a wide discrepancy between the size of the world known recoverable uranium resources and the assumed amounts of uranium in the earth’s crust. Figure 4 may suggest that only a tiny fraction of the world uranium resources has been discovered.
In the grade interval 1 - 0.1% U, for example, about 1.2 Tg of recoverable uranium resources are known, whereas the two bars in this grade interval in the histogram of Figure 4 add up to some 70 Tg. This observation would suggest that tens of millions of tonnes of uranium resources are waiting for discovery in this ore grade interval alone.

However, a closer look may lead to a less simple picture.
If we assume that the figures of Deffeyes & MacGregor refer to a 30 km thick crust and that deposits in the uppermost 1.5 km are mineable, then 1/20 of the amount in the grade interval 1 – 0.1% (70 Tg), or 3.5 Tg, would be mineable. Of that 3.5 Tg, 1.2 Tg are already mapped and classified as known recoverable. The balance of 2.3 Tg may be present at greater depths than the existing mines and/or in poorly explored areas, such as Antartica and Greenland.
From a statistical point of view the chances of finding new uranium deposits increase with decreasing ore grade, decreasing ore body size and increasing depth.

As the easily discoverable and easily mineable deposits are already known and in production (except a few ones perhaps), one may expect that new discoveries of significant uranium deposits may have lower energy quality than the currently known deposits of the same ore grade. The lower thermodynamic quality is due either to greater depth, longer transport distances, higher waste rock/ore ratios, more refractory uranium minerals, or other causes. Lower quality means more energy consumed per kg extracted uranium. Underground mining of uranium ores has to be done with robotic equipment, for reason of the high levels of radon and nuclear radiation from the rocks. Even the mining of very high-grade deposits may pose serious problems, requiring large investments of materials and energy, judging by the troubles at Cigar Lake in the Athabasca Basin in Canada.

Ore bodies tend to get poorer (i.e. lower metal content) and harder to mine, due to more refractory uranium minerals, with increasing depth, according to [Cook 1976] Q344. This phenomenon is, for instance,

observable in the current practice at the Ranger and Olympic Dam mines in Australia.
The distribution of uranium as function of the ore grade is not the sole parameter determining the thermodynamic quality of the ore: the depth, size and minerology of a given deposit

During the past decades no evidence has been published on the existence of major new uranium deposits of similar energy quality as the currently mined deposits, that would significantly extend the world uranium supply. The chances of finding a new Olympic Dam (very low grade, extremely large ore body) or Athabasca Basins (extremely high grade, medium sized ore bodies) are unknown.

Discovery of a new Athabasca Basin-like deposit would add some 7 years to the uranium supply from high-quality ores, at the current world consumption rate of around 68 Gg/yr. A new Olympic Dam-sized deposit would add around 17 years, but at a marginal energy quality. Bringing a large new deposit, not adjacent to an existing one, into production may take some 10 years.

Summarized:

- The easiest discoverable and easiest recoverable uranium resources are already discovered and almost all of them are already in production.
- During the past decades no evidence has been published on the existence of major new uranium deposits of the same energy quality as the currently mined deposits, that would significantly extend the world uranium supply.
- From a geological point of view the chances of finding major high-quality deposits seem not large.
- The chances of finding new uranium deposits increase with decreasing ore grade, decreasing ore body size and accessibility.
- Based on above considerations one may expect the yet-to-be discovered uranium deposits lying closer to the energy cliff, to be discussed in the next chapter.

4 Thermodynamic quality of uranium resources

Energy system

An energy system is defined as the system of technical processes and installations needed to convert the potential energy embedded in an energy carrier into useful energy, such as electricity. Energy conversions are a matter of thermodynamics, Thermodynamics is the science of energy conversions and is at the basis of all sciences, because any change in the observable universe is coupled with an energy conversion.

A simple thermodynamic rule states: the generation of useful energy costs energy. In practice that means that the conversion of the potential energy embodied in a mineral energy carrier into useful energy requires investments of useful energy. The nuclear energy system as a whole is no exception, it is a technical means to turn the potential energy in uranium nuclei into heat and the heat into electricity. The construction and operation of the nuclear energy system consume high-grade energy and materials. Useful energy has to be invested to generate useful energy. At issue is the energy return of energy investments: the EROEI, a quantity addressed in detail in report m35 *Energy cliff and CO2 trap*.
The sole mission of civil nuclear power is to supply the consumer and the economic system with useful energy to be used at will.

Any energy system requires useful energy and ordened materials to convert the potential energy present in a mineral resource or in a renewable source into useful energy. The nuclear energy system comprises all technical and industrial processes required to produce electricity from a uranium-bearing deposit in the earth's crust in the safest possible manner. All these processes consume useful energy (fossil fuels, electricity) and ordened, processed materials, such as chemicals and equipment.

Thermodynamic quality

Here we define the *thermodynamic quality* of a given uranium resource as the degree of usefulness of that uranium resource for net useful energy production. The net energy is the useful energy delivered to consumer, other than the useful energy required to construct, operate, maintain the nuclear installations of the nuclear system and to dismantle those installations at the end of their operational lifetime.

Methodology

In the literature widely different figures have published with regard to the specific energy consumption, and consequently the specific CO_2 emission, of the nuclear energy system [Sovacool 2008] Q372 in general and of the uranium recovery in particular. For that reason it may be helpful to explain briefly the methodology used in this study.

The energy analysis of this study of the recovery of uranium from its ores is based on a generic flowsheet of the mining and milling processes, analogous to the flowsheet of the Ranger mine in Australia. The mining and milling processes are discussed in detail in report m26 *Uranium mining + milling*.
By means of a process analysis the inputs of materials and energy are estimated for a world average uranium mine. The energy inputs comprise the direct energy inputs (fossil fuels and electricity) as well as embodied energy in materials and equipment. Embodied energy is the useful energy needed to produce the ordered materials (construction, chemicals) and equipment consumed by the energy system.
The full life cycle assessment (LCA) and energy analysis of the nuclear energy system from cradle to grave

are discussed in report 35 *Energy cliff and CO2 trap*. The CO_2 emission by the nuclear system as calculated in this study is exclusively originating from the burning of fossil fuels in the industrial processes constituting the nuclear energy system.

The recovery of uranium from the earth's crust requires a sequence of physical and chemical processes: mining, milling, leaching and chemical extraction. Each of these processes consume energy and materials and need equipment, the more so the lower the ore grade.
The energy required to produce pure uranium from the raw resources as found in nature varies widely, depending on the geological and mineralogical conditions of the deposits. Usually the ore grade is cited as the most important variable. Other important variables are: depth of the deposit below the surface, size of the deposit, mineralogy of the ore, transport distances and the availability of fresh water (uranium mining consumes large volumes of fresh water). High-grade deposits at great depth and in unstable geologic environment may have a high or even a prohibitive specific energy consumption (e.g. Cigar Lake in Canada). Unfortunately insufficient quantitative data are available in de open literature to define a quantitative ranking of uranium resources according to the ore quality, something like an 'ore grade-equivalent' which takes into account several other important variables in addition to the ore grade.

This study makes distinction between 'hard' and 'soft' ores. Hard ores require substantially more energy per kg recovered uranium than soft ores. Uranium ores tend to be harder to unlock at lower grades, physically and chemically (indicated by the color in Figure 5), due to a more refractory mineralogy of the uranium mineral and of the host rock.

Energy cliff

From the laws of thermodynamics follows the conclusion that the energy investment per kg uranium from a given uranium deposit increases with declining ore grade. Below a certain grade the useful energy investment may be as large as or larger than the useful energy generated by fission of the uranium from a certain deposit, even if other variables are ignored. If so, that uranium deposit is in effect no longer a net energy source, but an energy sink.

Figure 5 gives the relationship between net energy output of the complete nuclear energy system from cradle to grave and the ore grade of the uranium resources feeding the system. With declining thermodynamical quality. in this study only the ore grade is taken into account, the net energy output declines exponentially and approaches zero at a certain ore grade. This relationship, called the 'energy cliff'.is explained in report m26 *Uranium mining + milling* and is illustrated by Figure 6,

In the high end of the ore grade range (≥ 0.2%) the net energy produced by the nuclear system per kg uranium hardly depends on the ore grade, but at lower grades the net energy steeply drops to zero. The higher curves represent the net energy of the nuclear fuel chain only. The lower curves represent the full nuclear system, that is, fuel chain plus the construction and dismantling of the reactor. The decline of the curves with decreasing ore grade is solely due to the increasing energy input of the uranium recovery and reclamation of the mining area. At grades higher than 0.2% this input is of minor importance.

The energy cliff gives a clue on the thermodynamic quality of the known recoverable uranium resources. Deposits at grades of 0.02 – 0.01%, such as Valencia and Trekkopje in Namibia, have a thermodynamic quality approaching zero. The energy analysis of the uranium recovery proves that this observation is nearly independent on the choice of the system boundaries: the process chain only or the full system, including construction and dismantling.

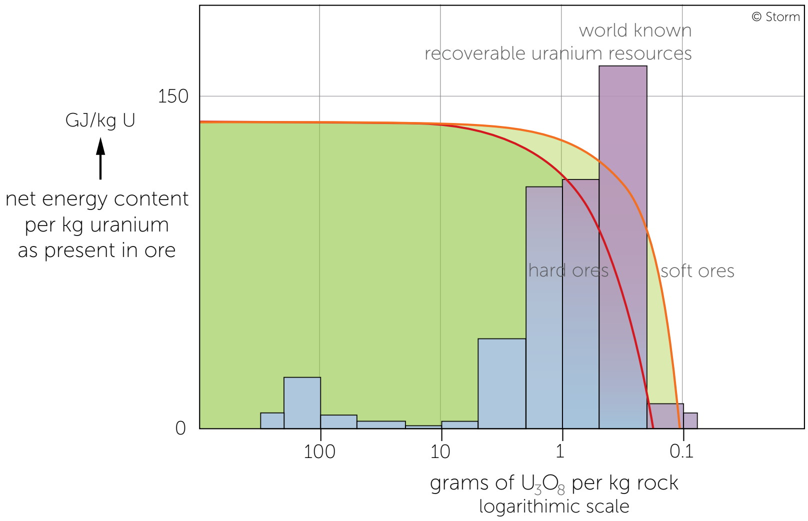

Figure 6

Energy cliff and the known uranium resources. The bar diagram shows the amounts of the world known recoverable uranium resources (in relative units) and their ore grade distribution in 2008. The red curve represents the net energy production (in arbitrary units) of the nuclear system from cradle to grave as function of the ore grade.

Net energy potential of uranium resources

Basically the amount of useful energy embodied in a given uranium deposit in the earth's crust is determined by two quantities:

- thermodynamic quality of the uranium deposit
- fraction of the natural uranium, as recovered from the deposit, that can be fissioned in the nuclear reactor.

The latter quantity depends on the reactor technology. In the current generation of power reactors of the world, mainly light-water reactors (LWRs), not more than 0.6% of the nuclei in natural uranium can be fissioned, with slight variations depending on the reactor type and age. Consequently the amount of energy that can be liberated from 1 kg natural uranium has a fixed value within small margins.

The earth's crust contains enormous amounts of uranium, dispersed in widely different rock types with grades ranging from more than 100 grams of uranium per kilogram rock to less than 1 milligram of uranium per kilogram rock. At grades lower than 0,2-0,1 grams of uranium per kilogram rock no net energy can be generated from a uranium deposit: the *energy cliff*. Obviously uranium can be extracted from rocks below the energy cliff, perhaps even economically justifiable under certain conditions, but extraction from those rocks generates an energy sink, not an energy source. This fact is not a matter of technology, but is determined by fundamental laws of nature.

From a quantative viewpoint the uranium occurrences of the world are practically inexhaustable. Actually the depletion of uranium resources as a source of useful energy is a thermodynamic notion.

5 Uranium resources - the industrial view

Uranium ore

The term 'ore' is an economic notion. An orebody is, by definition, an occurrence of mineralisation from which a given metal is economically recoverable. The qualification 'ore' is therefore relative to both costs of extraction and market prices [WNA-75 2010] Q85. The term 'reserves' is usually limited to estimated quantities of mineral materials considered economically recoverable with existing technology at a given market price. 'Resources' are defined as all naturally occuring uranium concentrations in a given geological environment, irrespective of economic considerations at a given moment.
The view of the nuclear industry with regard to the outlook of the world uranium resources is illustrated by the following quote from [WNA-75 2010] Q85:

> 'Of course the resources of the earth are indeed finite, but three observations need to be made:
> - first, the limits of the supply are so far away that the truism has no practical meaning.
> - Second, many of the resources concerned are either renewable or recyclable (energy minerals and zinc are the main exceptions, though the recycling potential of many materials is limited in practice by the energy and other costs involved).
> - Third, available reserves of 'non-renewable' resources are constantly being renewed, mostly faster than they are used.'

The concerns raised that the known resources might be insufficient when judged as a multiple of the present rate of use are designated by the nuclear industry as the 'Limits to Growth fallacy'. In their criticism on the views regarding depletion of mineral resources, the nuclear industry identifies three principal areas where resource depletion predictions would have faltered:

- 'predictions have not accounted for gains in geological knowledge and understanding of mineral deposits,
- they have not accounted for technologies utilised to discover, process and use them,
- economic principles have not been taken into account, which means that resources are thought of only in present terms, not in terms of what will be economic through time, nor with concepts of substitution in mind.'

Economic viewpoint

The nuclear industry bases its prospects of the future uranium supply mainly on an economic relationship between market price and the size of uranium resources. The economic point of view on mineral scarcity can be summarized as follows:
- The market price is the criterion of the mining of a metal or mineral.
- Higher prices will lead to more intensive exploration.
- More exploration will lead to more discoveries of new mineral deposits.
- The newly discovered deposits will contain more of the desired mineral than the already known deposits.
- At higher price more and larger resources are economically recoverable.

Ergo: the world mineral resources, in casu uranium resources, are practically inexhaustible.

Within the nuclear world an economic viewpoint with regard to the future uranium supply seems widely adopted. This view is based on a price-resource relationship in a model as illustrated by Figure 7.

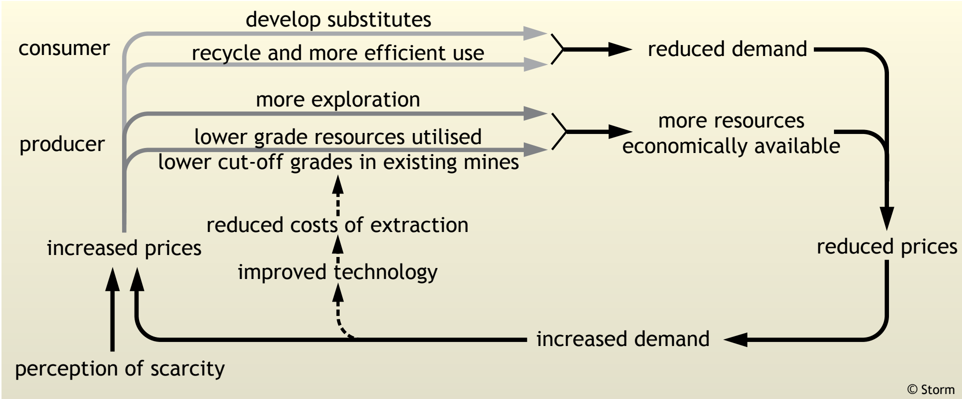

Figure 7

Economic adjustments in supply of a 'non-renewable' resource, i.e. uranium resources, according to [WNA-75 2008] Q85. In this economic view mineral resources are virtually inexhaustable. In effect the diagram is based on non-physical quantities, which are not unambiguously quantfiable. Physical boundaries, such as an energy input limit per unit product, are absent from this model.

Several authors, e.g.[Wikdahl 2004] Q285, [MacDonald 2001] Q286 and [MacDonald 2003] Q287, consider the uranium resources being virtually inexhaustable. By analogy with the oil industry, the nuclear world expects to discover new large and rich uranium resources when exploration will be resumed vigorously. Their views are based solely on economic considerations and by analogy with the oil industry: more exploration will yield more known resources. As [WNA-75 2010] Q85 puts it:

> "In recent years there has been persistent misunderstanding and misrepresentation of the abundance of mineral resources, with the assertion that the world is in danger of actually running out of many mineral resources. While congenial to common sense if the scale of the Earth's crust is ignored, it lacks empirical support in the trend of practically all mineral commodity prices and published resource figures over the long term. In recent years some have promoted the view that limited supplies of natural uranium are the Achilles heel of nuclear power as the sector contemplates a larger contribution to future clean energy, notwithstanding the small amount of it required to provide very large amounts of energy."

This opinion seems to be widely held within international nuclear institutes, such as WNA, OECD/NEA and IAEA.

The economic model illustrated by Figure 7 is largely based on non-physical quantities and notions, which are not unambiguously quantifiable. A fallacy that may cripple the model is that the energy content of uranium is not price-dependent. The amount of heat which can be released from 1 kg natural uranium – and so the amount of electricity generated – is a physical quantity with a fixed value, depending only on the type of reactor. With the current reactor technology about 0.5-0.6% of the nuclei in natural uranium can be fissioned. This fraction will remain so during the next decades. Breeder systems, which theoretically would be able to fission 30-60% of the nuclei, will not come on line in a foreseeable future, if ever.

Supply curves

The nuclear industry takes the view that a doubling of the price of a mineral from the present level could be expected to create about a tenfold increase in measured economic resources, over time, due both to increased exploration and the reclassification of resources regarding what is economically recoverable [WNA-75 2010] Q85. Apparently the nuclear industry is convinced that advancing technology will provide the solutions to currently existing and future recovery problems and that higher market prices will lead to discovery of new and larger resources. In part this view may be valid, but it is not the whole story.

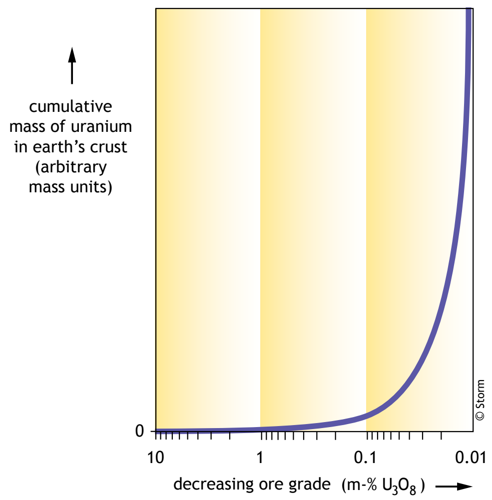

Figure 8

Hypothetical relationship between the amount of uranium present in the earth's crust and the decreasing ore grade. Note that the horizontal axis has a logarithmic scale and the vertical axis an linear scale.

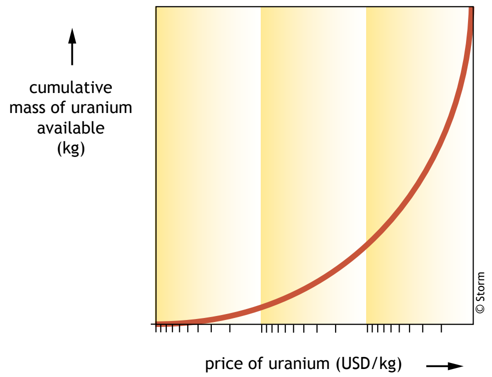

Figure 9

Hypothetical simple supply curve of uranium, according to [Deffeyes & MacGregor 1980] Q281. Note that the horizontal axis has a logarithmic scale and the vertical axis an linear scale. Deffeyes & MacGregor point out that other, less simple supply curves are also possible.

The smoothly ascending supply curve in turn is based on a smoothly ascending curve relating the amount of uranium present in the earth's crust and the decreasing ore grade, as illustrated by Figure 8. In fact this curve is the ascending part of a hypothetical log-normal distribution of uranium in the earth's crust. The assumption of the log-normal distribution being valid seems in turn to be based on the publication of [Deffeyes & MacGregor 1980] Q281 and their distribution diagram of uranium in the earth's crust, see Figure 9.

Any other distribution than the log-normal distribution likely will result in a more complex supply curve than Figure 9, such as illustrated by Figure 10.

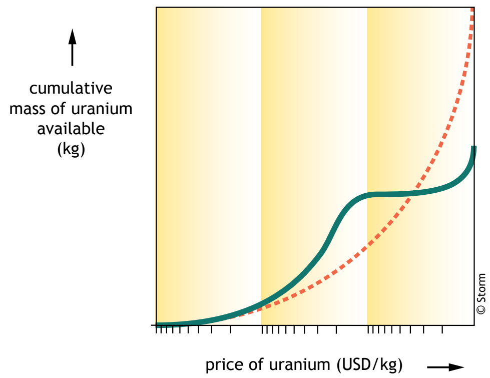

Figure 10

Hypothetical complex supply curve of uranium, according to [Deffeyes & MacGregor 1980] Q281. The dashed curve represents the simple supply curve from Figure 9. This kind of supply curve could apply to a mineral with a bimodal distribution.

If the supply curve of Figure 10 were to apply to uranium, a modest price increase would cause virtually all the uranium deposits in a given geological category to be discovered and mined. A very large price increase would then be necessary before another category would become exploitable. A bimodal distribution as illustrated by Figure 3 would cause the kind of discontinuity represented by the flat portion of the supply curve in Figure 10. Obviously such a discontinuity would have profound consequences for the long-term perspective of the uranium supply.
A vital question in regard to the long-term uranium supply is wether the crustal distribution of uranium could be best described by the bell-shaped log-normal curve of Figure 2, or by a bimodal (or even multimodal) distribution curve, such as in Figure 3. This issue has been addressed by Deffeyes & MacGregor.

There is an essential distinction between the notion of uranium as just a mineral and the notion of uranium as an energy source; this will be explained below.
Substitution of uranium by another mineral is no option, as uranium contains the only fissile atoms in nature, namely U-235. As is explained in report m24 *Thorium for fission power*, a civil energy system based on the use of thorium as fertile material to breed uranium-233, which is fissile, is a concept infeasible due to Second Law phenomenaon papercyberspace.

Uranium, being a geologically scarce metal, is a different commodity than a fossil fuel. The similarity ends with the observations that both uranium and fossil fuels are found in the ground and both have something to do with the generation of useful energy. The origins of uranium and fossil fuels are completely different, as are the geologic principles and mechanisms which formed the deposits of these commodities.
For that reason the application of an economic reserves-production relationship (supply curve) which may be valid in the oil industry, may not lead beforehand to the right conclusions in case of the uranium supply.

Just a mineral or an energy source?

The question at issue is: what is the meaning of the curves of Figures 8 and 9 , valid for uranium resources from a geologic-economic point of view, with regard to *energy* resources?

Unlike all other metals, uranium is exclusively used as energy source (setting aside military purposes), not as construction material, chemical or ornament. This implies that the criterion for extraction should be based on the energy required for the extraction of the uranium from the deposit. If the energy consumed in the production of one kg of uranium is more than the energy which can be generated from the same amount, the uranium resource cannot be considered an energy source.

Table 3

Abundancy of uranium in various geologic reservoirs. Uranium is one of the scarce elements and is about as common in the earth's crust as tin or zinc

occurrence	concentration (ppm = g U/Mg rock)	reference
high-grade ore, 2% U	20 000	WNA75 2007 [Q85]
low-grade ore, 0,1% U	1000	WNA75 2007 [Q85]
Chattanooga shales (average)	60	Boyd 1980 [Q156], Burnham et al. 1974 [Q136]
copper-, gold ores (by-product	50 - 500	UIC34 2003 [Q86], NAC 1982 [Q53]
phosphate ores	10 - 300	INFCE-1 1980 [Q226], Bergeret 1979 [Q47]
Conway granite	12 - 15	NEA/IAEA 1978 [Q48]
granite (average)	4	WNA75 2007 [Q85]
sedimentary rocks (average)	2	WNA75 2007 [Q85]
average continental crust	2.8	WNA75 2007 [Q85]
seawater	0.0034	ORNL 1974 [Q133]

[Mortimer 1979] Q118, [Mortimer 1980] Q122 and [Bowie 1975] Q49 conclude that G = 50 ppm U_3O_8 (50 g U_3O_8 /Mg ore) is the minimum grade for uranium-bearing rocks to be considered ores. [Brinck 1975] Q55 takes a cut-off grade of 200 ppm U_3O_8. One of the results of the energy analysis in this study, the energy cliff (see Figure 6) point to a cut-off grade of between 200-100 ppm U.

Geologic resources are distributed unevenly over the surface of the globe and they are concentrated in the outermost part of the earth's continental crust. Mechanisms that concentrate uranium operate most effectively on or near the earth's surface. Ore bodies tend to get poorer and harder to mine downward [Cook 1976] Q344. This phenomenon is, for instance, observable in the current practice at Ranger and Olympic Dam in Australia.

Empirical data show a relationship between the crustal abundance of a scarce metal and metal content of the largest found ore body of that metal [Uytenbogaardt 1980] Q319. If we apply this relationship on the case of uranium, with a crustal abundance of 2.7 ppm, the largest ore body expected to be found would contain over 1 Tg (1 Tg = one million metric tonnes) uranium. Actually an uranium ore body of that size is known: Olympic Dam in Australia, containing about 1.6 Tg uranium, albeit at very low grades.

Ore types

In addition to the uranium resources from conventional ores , [Red Book 2014] Q90 and [MIT 2003-2009] Q280 mention other geologic reservoirs as potential unconventional uranium resources, namely phosphates, shales and seawater. This section briefly introduces some practical aspects of the recovery of uranium from these reservoirs, which are addressed in detail in separate reports.

Conventional uranium resources

Conventional uranium resources are the resources that are currently being mined. These resources contain many different types of rock containing separate grains of uranium minerals. The uranium content may vary from more than 10% U to about 0.01% U.

Unconventional uranium resources
Vast amounts of uranium are known to be present in black shales, phosphate rock, lignite and coal. Due to the low grades, typically less than 0.1 gram per kilogram rock, extremely large amounts of the uraniferous deposits would have to be mined and processed. The energy consumed in the uranium extraction would push the nuclear energy system off the energy cliff (see report m35 *Energy cliff and CO2 trap*.
Extraction of uranium from unconventional resources would inflict extensive damage to vast areas because exceedingly large volumes of the uranium-containing minerals would have to be excavated and processed, due to their very low uranium content. Phosphates are an irreplaceable ingredient of fertilizer and should be recovered exclusively for use in agriculture.
These issues are addresed in report m27 *Unconventional uranium resources*.

Uranium from seawater
The Earth's oceans are containing billions of tons of uranium, an inexhaustable uranium source. Nuclear industry's optimistic view with regard to the possibilities of extraction of uranium from seawater is based on laboratory-scale experiments, untried technology, unproven assumptions and a billion-fold upscaling of a few experiments. In fact the optimistic view is based on ignorance of the Second Law of thermodynamics. The consumption of materials and energy per kilogram extracted uranium would be prohibitive, as is explained in report m28 *Uranium from seawater*.

Presently a few minor phosphate mines are producing uranium as byproduct. Large-scale uranium recovery from phosphates Otherunconventional uranium resources are not exploited and will not be in the foreseeable future.

Mining costs and ore grade

Figure 11 shows the empirical relation between production costs and ore grade; the diagram is based on data of all operating uranium mines outside China and the former Sovietunion in 1982 [NAC 1982] Q53. The total amount of these resources was 1.8 Tg uranium. Unfortunately, we could not update Figure10, because recent data from the Nuclear Assurance Corporation are not free. Anyway, the diagram gives an impression of the ore grades of the most uranium mines.

Notable aspects are, among others: the rough relationship between ore grade/production costs, and the large spread in production costs. It may be interesting to note that the reported value of, for example, Ranger of 11.22 $/lb U_3O_8 in 1982 would correspond with 29.17 $/kgU (1982), or about 61 $/kgU in $(2006).

Figure 11 shows that most uranium mines known in 1982 have ore grades in the range of 0.08 -0.4% U_3O_8. This is still the case, although a trend to lower ore grades is observable. This is not to say that the largest resources are in that grade range. The largest known resources have grades in the range of 0.02-0.05% U.

Since 1982 few new deposits are added: in Canada relatively large ore bodies with high ore grades (up to 20% U_3O_8) came into production (McArthur River and Cigar Lake, estimated at about 344 Gg uranium), and there are some new discoveries in Brazil (256 Gg uranium). Some mines from the list in 1982 now are closed or mined out (e.g. Nabarlek and Yeelirrie), but most are still in operation today. The main differences in the total known resources in 2006, compared with those in 1982, are the inclusion of resources not included in the 1982 list (e.g. China, Russia, Uzbekistan, Kazakhstan). In addition the size of some known resources in Australia, particularly Olympic Dam, have been greatly upgraded during the past years.

Striking is the absence of exploited ore bodies with grades in the range of 0.5 – 1.0% U_3O_8. Today only one deposit with a grade in this interval is known to be mined: Key Lake with 0.254 Gg at 0.53% U_3O_8. In 1982 Key Lake reportedly contained some 58 Gg uranium at a grade of 2.27% U_3O_8, so the 2006 data may refer to a downgraded remainder of the original Key Lake deposit.
Also notable are the small number of mined deposits with grades of 1% U_3O_8 or higher. Since 1982 a few are added to the list, nearly all located in one geologic province, the Athabasca Basin in Canada. Nabarlek in Australia has been mined out.

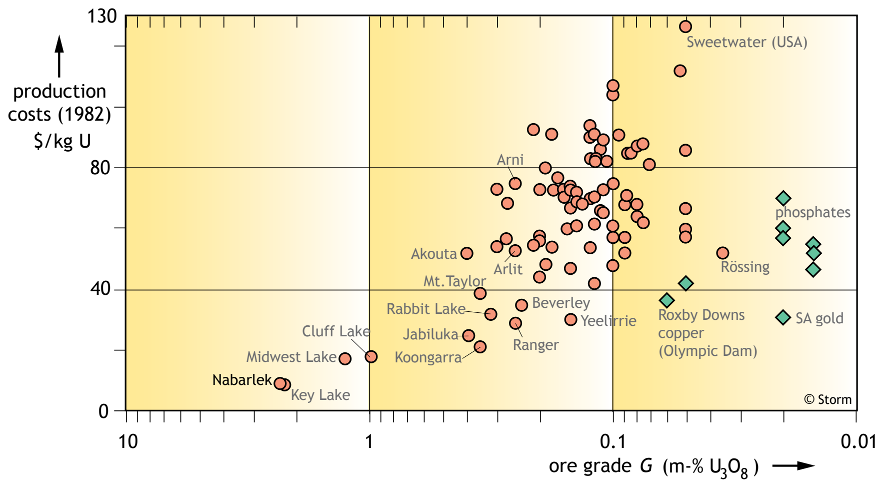

Figure 11

Ore grade and production costs of operating uranium mines of the world, except China and the former Sovietunion in 1982. Based on data from [NAC 1982] Q53. The diamonds represent mines where uranium is extracted as by-product of copper, gold or phosphates.

6 Recoverable uranium resources

Resource terminology

The term '*ore*' has an economic definition. A mineral deposit is called an ore when the metal from that deposit can be recovered in a economically profitable manner. Two factors must be considered in defining and appraising mineral resources:

- the degree of geological assurance of their existence and size: the quantitative aspect
- the feasibility of recovery in existing economic and technological conditions: the qualitative aspect.

The term *'reserves'* is usually limited to estimated quantities of mineral materials considered economically recoverable with existing technology.
'*Resources*' are defined as all naturally occuring mineral concentrations in a given geological environment, irrespective of economic considerations.
Several aspects contribute to the designation 'recoverable resource' of a given mineral, such as: the natural availability, the geographic distribution, the cost of extraction, processing and transport of the mineral, the production capacities and potential of the mines, the market price of uranium and the financial and politcal climate at the location of the mine.

Uranium resources are broadly classified as either conventional or unconventional. Below the definitions according to the NEA/IAEA [Red Book 2014] Q90.
Conventional resources are those that have an established history of production where uranium is, either, a primary product, co-product or an important by-product (e.g., from the mining of copper and gold). Very low-grade resources or those from which uranium is only recoverable as a minor by-product are considered unconventional resources.
The conventional resources are further divided into four categories, according to different confidence levels of occurrence. The four confidence categories are further subdivided into categories based on production cost. Within the uranium industry six classification systems of uranium resources are in use and one of them is the NEA/IAEA classification system, see Figure 12. The following definitions are quoted from NEA/IAEA Red Book 2014.

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

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

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

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

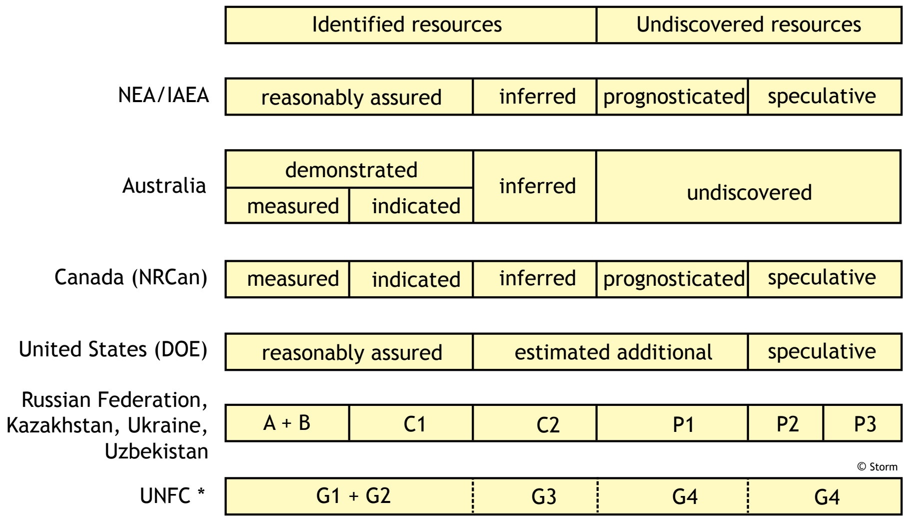

Figure 12

Approximate correlation of terms used in major resources classification system. The terms illustrated are not strictly comparable as the criteria used in the various systems are not identical. “Grey zones” in correlation are therefore unavoidable, particularly as the resources become less assured. Nonetheless, the chart presents a reasonable approximation of the comparability of terms. Source: NEA/IAEA [Red Book 2011 and 2014] Q90.

* Work to align the NEA/IAEA and national resource classification systems outlined above with the United Nations Framework Classification system (UNFC) remains under consideration.

Cost categories

The cost categories, in United States dollars (USD), used in Red Book are defined as: up to 40 US$/kg U, up to 80 US$/kg U, up to 130 US$/kg U and up to 260 US$/kg U. All resource categories are defined in terms of costs of uranium recovered at the ore processing plant.
When estimating the cost of production for assigning resources within these cost categories, account has been taken of the following costs:

- direct costs of mining, transporting and processing the uranium ore;
- costs of associated environmental and waste management during and after mining;
- costs of maintaining non-operating production units where applicable;
- in the case of ongoing projects, those capital costs that remain non-amortised;

- capital cost of providing new production units where applicable, including the cost of financing;
- indirect costs such as office overheads, taxes and royalties where applicable;
- future exploration and development costs wherever required for further ore delineation to the stage where it is ready to be mined;
- sunk costs are not normally taken into consideration.

Note: It is not intended that the cost categories should follow fluctuations in market conditions.
As mentioned above, other factors may play a part, such as the financial and politcal climate at the location of the mine.

World known recoverable uranium resources

Table 4
World known recoverable resources of uranium. Reasonably Assured Resources (RAR) plus Estimated Additional Resources (EAR)-category 1, to 80 US$/kgU for the year 2005. Identified Resources (= Reasonably Assured Resources (RAR) plus Inferred Resources (IR)) to 130 US$/kgU for the years 2006 and 2008. identified resources (RAR and Inferred) to 130 US$/kgU and 260 US$/kgU for the year 2013

	2005 * ‹ 80 US$/kg U		2006 ** ‹ 130 US$/kg U		2008 *** ‹ 130 US$/kg U		2013 **** ‹ 130 US$/kg U		2013 **** ‹ 260 US$/kg U	
	Gg U	%	Gg U	%	Gg U	%	Gg U	%	Gg U	%
Australia	1074	30	1143	24	1243	23	1706	29	1798	24
Kazakhstan	622	17	816	17	817	15	679	12	875	11
Canada	439	12	444	9	423	8	494	8	651	9
South Africa	298	8	341	7	435	8	338	6	451	6
Namibia	213	6	282	6	275	5	383	6	456	6
Brazil	143	4	279	6	278	5	276	5	276	4
Niger			225	5	274	5	405	7	405	5
Russian Federation	158	4	172	4	546	10	506	9	689	9
USA	102	3	342	7	339	6	207	4	472	6
Uzbekistan	93	3	116	2	111	2	91	2	91	1
Ukraine			90	2	200	4	118	2	223	3
Jordan			79	2	112	2	40	1	40	1
India			67	1	73	1	NA	–	120	2
China			60	1	68	1	199	3	199	3
Mongolia					62	1	142	2	142	2
Botswana							69	1	69	1
Czech Republic							0	–	119	2
Greenland							0	–	221	3
Tanzania							58	1	58	1
Other	480	13	287	6	213	4	191	3	280	4
Total world	3622	100	4743	100	5469	100	5903	100	7635	100

1 Gg = 1 gigagram = 10^9 gram = 1000 metric tonnes.
The percentages may not sum up exactly to 100, due to rounding of the figures.

* [WNA-75 2005] Q85 and [WNA-48 2005] Q210, from update February 2006.
** NEA/IAEA [Red Book 2006] Q90.
*** NEA/IAEA [Red Book 2006] Q90
**** NEA/IAEA [Red Book 2014] Q90

Few discoveries of uranium deposits have been added to the listed resources since 2005. Very few new resources, if any, are discovered during the last decades anyway. It is important te note that the bulk of the increases are due to re-evaluations reflecting the effects of higher uranium prices: reclassification of previously known unrecoverable resources into 'recoverable' resources and, for example by lowering the cut-off grades [Red Book 2006] Q90. For example, in 2006 the Ranger mine in Australia lowered its cut-off grade from 0.12% to 0.08% U_3O_8, thus increasing its resources by 6000 Mg U [ERA 2006] Q320.

The market price of uranium has been less than 100 USD/kg U for the past several years through 2014.

Undiscovered resources

Total undiscovered resources (*prognosticated resources* and *speculative resources*) as of 1 January 2013 amounted to 7.7 Tg U, a significant decrease from the 10.4 Tg U reported in 2011. According to NEA/IAEA Red Book 2014 [Q90] principally because the United States did not report data for this edition as previous estimates completed in 1980 need re-evaluation to determine their accuracy.
The sum of the Identified Resources + Undiscovered Resources = 7.6 + 7.7 = 15.3 Tg U per 1 January 2013.

An estimate based on a geological rule of thumb amounts to 27-270 Tg uranium in uranium minerals in the Earth's crust to a depth of 2.5 km. Uytenbogaardt and Brinck cite only the lower values: 27 Tg or less.
Mining of uranium ore at depths of 2.5 km seems unrealistic, even a depth of 1 km may pose serious problems. At depths of more than, say, 500 meters, only underground mining is a viable option. Haulage of large masses of ore to the surface from underground mines requires much energy and equipment, the more energy per kg uranium the lower the ore grade. The deeper the mine, the higher the ore grade must be to make the mining profitable, from the economic point of view as well from the energetic point of view. At high grades the ore has to be mined by remotely controlled equipment, due to the high radiation and radon levels in the mine. At a given depth a point may be reached below which no uranium mining with a positive net energy balance is possible, even if the ore would consist of pure uraniumoxide.
If we consider, more or less arbitrarely, only uranium mineral deposits in the upper one km of the crust, the theoretically inferred uranium resources may be in the range of 11-110 Tg. In practice this amounts will be lower, as large parts of the continental crust are not very amenable to uranium mining. The reported IR + UR of 15.3 Tg fits within well with above range.

The classification systems do not give a clue on the thermodynamic quality of those uranium resources. After all that is the only criterion of a uranium resource for being an energy source or an energy sink.

7 Long-term perspective

Supply potential

Apparently the nuclear industry and the IAEA see little or no limitations for the future development of nuclear power. Even without a closed fuel cycle, the available uranium resources would be sufficient to support the current nuclear fleet for many hundreds of years. A considerable expansion of the current nuclear fleet would be possible without constraints. This view is illustrated by the nuclear scenarios of the IAEA and WNA, see report m10 *Global context and prospects of nuclear power*, and by Table 5.

The sum of conventional resources per 01-01-2013 was 15.3 Tg, slightly more than the figure of 14.7 Tg per 01-01-2005 in Table 5. The world annual uranium consumption in 2006 was 68 Gg/a, in 2012 the annual consumption was about 62 Gg.

Table 5 is based on Table 27 from the Red Book 2006. Notably this table has been omitted from the following editions of the Red Book. Although breeders and closed cycle systems are mentioned, the IAEA/NEA does not translate their statements into numbers in a table, as they did in Red Book 2006. Still this kind of figures, 100‘s to 1000‘s of years of nuclear potential, frequently pop up in the present publications of the nuclear industry.

Table 5

Uranium resources and R/P ratios (resource/production ratios), or years of supply, according to the NEA/IAEA [Red Book 2006] Q90 and [Omoto 2007] Q359.

categories of resources (1) per 01-01-2005	uranium (Tg)	years LWR once through (2)	years LWR 68 Gg/a (3)	years fast reactor closed cycle (4)
identified resources (IR)	4.7	85	69	2570
undiscovered resources PR + SR	10	185	147	5445
sum conventional resources	14.7	270	216	8015
phosphates	22	405	324	11925
sum conventional + phosphates	36.7	675	540	19930

(1) IR = Identified Resources, PR = Prognosticated Resources, SR = Speculative Resources.

(2) According to the IAEA Red Book 2006. Apparently the IAEA assumes an annual consumption of 55 Gg/a in the base year 2004.

(3) The world consumption rate of natural uranium in 2006 was some 68 Gg/a. This column is added by the authors of this study.

(4) [Omoto 2007] cites figures of 8000-16000 years from conventional resources only and 20000-40000 years of supply from conventional resources + phosphates when used in closed-cycle fast reactor system.

Other uranium resources

As the name implies, no assurance exists with regard to the Undiscovered Resources. Unclear is how these estimates came about and no clues on the ore quality have been published by NEA/IAEA.

The sum of the Identified and Undiscovered Resources is 15.3 Tg (per 01-01-2013). This number seems to be used without reservations in publications of the nuclear industry regarding the nuclear future, as if these resources are assured and as if the only uncertainty is the price of uranium on the global market, see for instance [Omoto 2007] Q359. The IAEA states that these so-called conventional uranium resources will last for several hundred years at the current consumption rate.

In addition to the Undiscovered Resources, the IAEA states that beyond the conventional uranium resources abundant uranium (22 Tg) will become available in phosphates and ultimately in seawater: 4000 Tg.
The conventional resources plus the phosphates would last for 6-7 centuries at the current consumption rate. With fast reactors these resources would last for 8000 - 16000 years. How valid are these assertions?
The recovery of uranium from phosphates, shales and seawater will be discussed in reports m27 *Unconventional uranium resources* and m28 *Uranium from seawater*.

Technical promises versus realism

Today's nuclear power is almost exclusively generated by thermal neutron reactors, 88% of which are light-water reactors (LWR). In these reactors a small fraction of the atoms in natural uranium can be fissioned, in practice not more than 0.5 - 0.6%. The other 99.4% end up in the waste: depleted uranium and spent fuel. Closed-cycle reactor systems in which a significantly larger fraction (30-60%) of natural uranium would be fissionable are uranium-plutonium breeder systems,

Presently the closed-cycle reactor is usually designated 'fast reactors' because the name 'breeder' has got the connotation of a failed technology from the 1970s-1990s. Fifty years of research in seven nations, with spending of some 100 billions of dollars, did not result in one working breeder cycle. There is no empirical evidence that the breeder system ever will be feasible. On the contrary, from the Second Law of thermodynamics follows that the breeder cycle as envisioned by the nuclear industry is not possible. Report m01 *Uranium-plutonium breeder systems* addresses this issue in detail.
Prognoses of world nuclear power based on breeder systems, as given in the last column of Table 5, do not have any practical meaning.
Therefore, the global prospects of nuclear power should be based on the light-water reactor (LWR) in the once-through mode, as [MIT 2003-2009] Q280 states. The differences between the LWR and other currently used power reactors, e.g. CANDU reactors, are not relevant in the context of this study. This study is based on the LWR in the once-through mode.

The figures and statements of IAEA, NEA and MIT 2003-2009 with regard to the long-term perspective on uranium resources need to be examined in more detail for two reasons:

- Not all figures are as solid as may be suggested. Just the first three figures in the first row of Table 5 are based on proven evidence. All other figures are based on assumptions, speculations and concepts existing only on paper.
- The absence of any physical/chemical notion with regard to the thermodynamic quality of the uranium resources (see Chapter 4 of this report).

References

Q47
Bergeret 1979
Bergeret M,
Recovery of uranium from phosphates,
paper in:
Uranium and nuclear energy,
Proceedings of the Fourth International Symposium,
The Uranium Institute, London, September 1979
Published by Mining Journal Books Ltd, London, 1980.

Q48
NEA-IAEA 1978
OECD/NEA - IAEA
World uranium potential – an international evaluation,
OECD, Paris, December 1978.

Q49
Bowie 1975
Bowie SHU,
Some facts and fancies on uranium availability,
paper in:
Grenon M, editor
'Energy Resources'
Proceedings of the First IIASA Conference on Energy Resources,
Laxenburg, Austria, May 1975,
IIASA, CP-76-4, pp 649-652.

Q53
NAC 1982
Data world uranium mines outside China and Sovietunion,
Nuclear Assurance Corporation, Zürich, 1982
personal communication via PJ vander Hulst, KEMA, Arnhem.

Q55
Brinck 1975
Brinck JW,
Uranium resources assessment with 'Mimic': a descriptive model of mineral resources and long-term price trends in the mining industry,
paper in:
Grenon M, editor
'Energy Resources'
Proceedings of the First IIASA Conference on Energy Resources,
Laxenburg, Austria, May 1975,
IIASA, CP-76-4

Q85
WNA-75 2010
Supply of Uranium,
Appendix 1: The sustainability of mineral resources (September 2005)
Appendix 2: Mineral resources and reserves.
World Nuclear Association, December 2010
www.world-nuclear.org/info/inf75.html

Q86
UIC-34 2005
Geology of uranium deposits,
Uranium Information Centre, Nuclear Issues Briefing Paper # 34, November 2001 (site visit 8sept2005)
www.uic.com.au/nip34.htm
= [WNA26 2005]
World Nuclear Association, Information Paper # 26
www.world-nuclear.org/info/inf26.html

Q87
WNA-mining 2005
Uranium mining in Australia and Canada
World Nuclear Association, update March 2007
www.world-nuclear.org/education/mining.html

Q90
Red Book 2006
Uranium 2005: Resources, Production and Demand,
A joint report by the OECD NEA and International Atomic Energy Agency (IAEA), "Red Book"
NEA No. 6098, OECD 2006.

Red Book 2008
Uranium 2007: Resources, Production and Demand,
A joint report by the OECD NEA and International Atomic Energy Agency (IAEA), "Red Book"
Nuclear Energy Agency – Organisation for Economic Co-operation and Development,
NEA No. 6445, OECD 2008.

Red Book 2014
Uranium 2007: Resources, Production and Demand,
A joint report by the OECD NEA and International Atomic Energy Agency (IAEA), "Red Book"
Nuclear Energy Agency – Organisation for Economic Co-operation and Development,
NEA No. 7209, OECD 2014.

Q118
Mortimer 1979
Mortimer N D,
Energy analysis applied to uranium resource estimation (A paper from the floor),
Paper in:
Uranium and nuclear energy,
Proceedings of the Fourth International Symposium held by the Uranium Institute,
London, September 10-12 1979.
published by Mining Journl Books Ltd, London, 1980, pp 79-92.

Q122
Mortimer 1980
Mortimer N D,
'Uranium resource economivs. An application of energy analysis',
Resources Policy, March 1980, pp 19-32.

Q133
ORNL 1974
Harrington FE, Salmon R, Unger WE, Brown KB, Coleman CF & Crouse DJ,
Cost commentary on a proposed method for recovery of uranium from seawater,
ORNL-TM-4757,
Oak Ridge National Laboratory, November 1974.

Q136
Burnham et al. 1974,
Burnham JB, Brown RE, Enderlin W, Hanson MS, Hartley JN, Hendrickson PL, Paasch RK, Rickard WH, Schrenkhise RG & Watts RL,
Assessment of uranium and thorium resources in the United States and the effect of policy alternatives,
PN-238-658,
Battelle Pacific Northwest Laboratories, Richland, Washington: December 1974.

Q156
Boyd 1980
Boyd B W,
The future contribution of unconventional sources of natural uranium to nuclear fuel supply,
in: Colloque C2 Ressources energétiques,
26e Congrès Géologique International, Paris, 1980,

Editors PF Burollet & V Zigler,
Revue de l'Institute Française du Petrole,
Mars-Avril 1980, Mai-Juin 1980,
Vol. XXXV no. 2 & 3
Editions Technip, 27 Rue Grinoux, Paris.

Q210
WNA-48 2006
Australia's uranium and who buys it,
World Nuclear Association, February 2006
www.world-nuclear.org/info/inf48.html
identical with:
Uranium Information Centre, Nuclear Issues Briefing Paper 1,
February 2006,
www.uic.com.au/nip01.htm

Q211
UIC-emine 2005
Australia's uranium mines
Uranium Information Centre, December 2005
www.uic.com.au/emine.htm
website no longer existent,
Uranium Information Center replaced by Australian Uranium
Association AUA,
above paper not found, likely replaced by other, such as:
Australian_Uranium_Deposits_and_Resources.pdf (not dated,
probably 2008/2009)
www.aua.org.au/
retrieved Sept. 2011

Q212
WNA49 2011
Uranium in Canada,
World Nuclear Association, May 2011,
www.world-nuclear.org/info/inf49.html
retrieved Sept 2011

Q213
UIC-pmine 2005
Australia's uranium deposits and prospective mines
Uranium Information Centre, May 2005 › August 2005
www.uic.com.au/pmine.html

Q226
INFCE-1 1980
International Nuclear Fuel Cycle Evaluation,
Fuel and heavy water availability,
Report of INFCE Working Group 1,
STI/PUB/534,
International Aromic Energy Agency IAEA, Vienna, 1980.

Q280
MIT 2003-2009
Deutch J et al.,
The Future of Nuclear Power. An Interdisciplinary MIT Study,
Massachusetts Institute of Technology, Cambridge MA, USA,
2003
ISBN 0-615-12420-8
http://www.mit.edu/afs/athena/org/n/nuclearpower/pdf
Update 2009
http://web.mit.edu/nuclearpower/

Q281
Deffeyes & MacGregor 1980
Deffeyes K S & MacGregor I D
'World Uranium Resources',
Scientific American, 242 (1), 1980, pp 50-60.

Q285
Wikdahl 2004
Wikdahl C E,
Uranium – a sustainable energy source,
The Analysis Group, Fact Series, December 2004, annual volume
8,
www.analys.se

Q286
MacDonald 2001
MacDonald C,
Rock to reactors: uranium exploration and the market,
World Nuclear Association Annual Symposium 2001,
www.world-nuclear.org/sym/2001/macdonald.htm

Q287
MacDonald 2003
MacDonald C,
Uranium: sustainable resource or limit to growth?,
World Nuclear Association Annual Symposium 2003,
www.world-nuclear.org/sym/2003/macdonald.htm

Q314
WNA-27 2014
In situ leach (ISL) mining of uranium
World Nuclear Association, June 2003, updated July 2014
www.world-nuclear.org/info/inf27.html

Q319
Uytenbogaardt 1980
Uytenbogaardt W,
'Economische geologie in hoofdlijnen' (Outline of economic
geology),
Synopsis, Technical University Delft, March 1980 (in Dutch).

Q320
ERA 2006
Energy Resources of Australia Ltd (ERA),
Ranger Operation,
2006,
http://www.energyres.com.au

Q322
Skinner 1979
Skinner B J.
'Earth resources',
Proc.Natl.Acad.Sci.USA, vol 76, no 9, pp 4212-4217, September
1979.

Q324
WISE-U 2008
WISE Uranium Project,
www.wise-uranium.org

Q334
DRDGold 2005
Blyvooruitzicht Operation Analysts Visit 9 September 2005,
www.drd.co.za/ir/presentations.asp

Q344
Cook 1976
Cook E,
Limits to exploitation of non-renewable resources,
Science, vol 191 (1976), pp 676-682.
www.eoearth.org

Q354
ODX 2007
BHPBilliton
'Olympic Dam Expansion',
http://odx.bhpbilliton.com/expansion/index.asp

Q359
Omoto 2007
Omoto A,
Global Trends in Nuclear Power and Fuel Cycle and IAEA
Activities,
IAEA Presentation, 11 April 2007,
www–pub.iaea.org/MTCD/Meetings/PDFplus/2007/cn161/
Presentations/Presentation%20material/Omoto.pdf

Q367
Forsys 2007
Valencia Uranium Deposits
www.forsysmetals.com/valencia.htm
Snowden,
Forsys Metals Corp: Valencia Project, Namibia,
June 2007
www.forsysmetals.com/Theme/Forsys/files/
Valencia43101June07.PDF

Q369
Areva 2007
Reference Document 2007,
Areva, Financial Communications Department, 2008,
www.areva.com

Q370-a
Turgis 2008a
Trekkopje ESIA,
Turgis Mining Consultants, November 2007,
www.turgis.co.za/

Q370-b
Turgis 2008b
TrekkopjeEIA,
Turgis Mining Consultants, November 2007,
www.turgis.co.za/

Q371
IAEA 1996
Guidebook to accompany IAEA map: world distribution of uranium deposits,
STI/PUB/1021
IAEA, Vienna, 1996

Q372
Sovacool 2008
Sovacool B K,
Valuing the greenhouse gas emissions from nuclear power: A critical survey,
Energy Policy 36 (2008), p.2940-2953.

Q388
Skinner 2001
Skinner B J,
Exploring the resource base,
Workshop "The long-runavailability of minerals",
Resources for the Future (RFF), Washington DC, April 22-23, 2001.
http://www.rff.org