The Future of Nuclear Energy: Facts and Fiction - Part III: How (un)reliable are the Red Book Uranium Resource Data?

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For more than 40 years, the Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD) and the International Atomic Energy Agency (IAEA) of the United Nations have published a bi-annual document with the title "Uranium Resources, Production and Demand." This book, known as the IAEA/NEA 2007 Red Book, summarizes data about the actual and near future nuclear energy situation and presents the accumulated world-wide knowledge about the existing and expected uranium resources. These data are widely believed to provide an accurate and solid basis for future decisions about nuclear energy. Unfortunately, as it is demonstrated in this article, they do not.

The conventional world-wide uranium resources are estimated by the authors of the Red Book as 5.5 million tons. Out of these, 3.3 million tons are assigned to the reasonably assured category, and 2.2 million tons are associated with the not yet discovered but assumed to exist inferred resources. Our analysis shows that neither the 3.3 million tons of "assured" resources nor the 2.2 million tons of inferred resources are justified by the Red Book data and that the actual known exploitable resources are probably much smaller.

Despite many shortcomings of the uranium resource data, some interesting and valuable information can be extracted from the Red Book. Perhaps most importantly, the Red Book resource data can be used to test the "economic-geological hypothesis," which claims that a doubling of uranium price will increase the amount of exploitable uranium resources by an even larger factor. The relations between the uranium resources claimed for the different resource categories and their associated cost estimates are found to be in clear contradiction with this hypothesis.

(Links to 1st and 2nd parts)

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1. Introduction

Policy makers almost never discuss uranium resources and many other important resource issues in public. One reason seems to be that most energy resources are still considered to be a non-issue, and consequently, are ignored by world-wide policy makers and their economic or academic advisors.

The rapid increase in crude oil prices in the spring of 2008 has led to an attitude change with respect to the oil resource situation. Ever more people start to pay attention to questions of geological and technological limits to oil extraction capacities. This has resulted in the wish to obtain accurate oil and gas resource data, especially from the OPEC countries [1].

In contrast, the uranium resources appear to be accurately documented in the *Red Book: Uranium Resources, Production and Demand*. In this book, updated every two years, the IAEA (International Atomic Energy Agency) of the United Nations together with the NEA (Nuclear Energy Agency) of the OECD countries have presented, for more than 40 years [2], their collective knowledge about uranium resources and its use for civilian nuclear energy. The latest update, the 2007 edition, was published in June of 2008 [3]. This book provides more than 400 pages of detailed information about uranium resources in a large number of countries. A long history of reporting world-wide uranium resource data with an indicated accuracy of between 1/1000 and 1/10,000 is believed to demonstrate that reliable resource data are available. The findings of the Red Book 2007 edition were presented for example in a NEA press communiqué [4] as follows:

> There is enough uranium known to exist to fuel the world's fleet of nuclear reactors at current consumption rates for at least a century, according to the latest edition of the world reference on uranium published today. Uranium 2007: Resources, Production and Demand, also known as the Red Book, estimates the identified amount of conventional uranium resources which can be mined for less than USD 130/kg* to be about 5.5 million tons, up from the 4.7 million tons reported in 2005. Undiscovered resources, i.e. uranium deposits that can be expected to be found based on the geological characteristics of already discovered resources, have also risen to 10.5 million tons. This is an increase of 0.5 million tons compared to the previous edition of the report. The increases are due to both new discoveries and re-evaluations of known resources, encouraged by higher prices. (* On 26 May 2008, the spot price for uranium was listed as USD 156/kg.)

After reading such a declaration, most people will obviously assume that the uranium supply situation is safe. Why should one even bother to look into the accumulated uranium data or doubt these well respected international organizations with their large scientific staff? As a consequence, individuals and organizations with different philosophical views about nuclear energy almost never question the objectivity and precision of these data [5].

Unfortunately, as shall be shown in the following, the Red Book uranium resource data do not measure up to their indicated levels of accuracy.

In this article, the third part of *The Future of Nuclear Energy* [6], we analyze the uranium resource data given in the Red Book 2007 [3]. First, we present and discuss the overall world-wide uranium resource data and their evolution in Section 2. In order to investigate the basis for these data, the uranium resource data for the 10 countries with more than 100,000 tons of reasonably assured resources (RAR) are analyzed in Section 3. Combined, these 10 countries represent about 80% of the world's total RAR and 95% of those RAR that are most economical, i.e., RAR that can be economically produced at a price of < 40 dollars/kg. As shall be demonstrated in detail, the Red Book 2007 uranium resource data often exhibit amazing changes with respect to previous Red Book editions, with some of these individual country resource changes appearing to be totally unbelievable.

In Section 4 of this article, the long-term uranium supply situation and its consequences for the future of conventional nuclear fission power plants will be summarized.

2. World-wide uranium resources and their evolution

As highlighted already in parts I and II of this report, the authors of the Red Book do not ignore the possibility that "uranium supply shortfalls could develop if production facilities are not implemented in a timely manner." However, the media have essentially only reported the statement that "the identified conventional uranium resources have increased from 4.7 million tons in the previous edition to 5.5 million tons in the current edition of the Red Book." In the following, we shall analyze this apparent 20% increase in conventional uranium resources in detail. In order to do this, we start with the methodology on how the authors of the Red Book obtain their data and present the definitions of the different uranium resource categories.

2.1. Red Book methodology, resource categories and extraction costs

The authors of the Red Book describe the content and the methodology to obtain the relevant data in their own words as follows [7]:

> "The Red Book features a comprehensive assessment of current uranium supply and demand and projections to the year 2030. The basis of this assessment is a comparison of uranium resource estimates (according to categories of geological certainty and production cost) and mine production capability with anticipated uranium requirements arising from projections of installed nuclear capacity. In cases where longer-term projections of installed nuclear capacity were not provided by national authorities, projected demand figures were developed with input from expert authorities... The Red Book also includes a compilation and evaluation of previously published data on un conventional uranium resources... This publication has been prepared on the basis of data obtained through questionnaires sent by the NEA to OECD member countries (19 countries responded) and by the IAEA for those states that are not OECD member countries (21 countries responded and one country report was prepared by the IAEA Secretariat). The opinions expressed in Parts I and II do not necessarily reflect the position of the member countries or international organizations concerned. This report is published on the responsibility of the OECD Secretary-General."

In Appendix 2 of the Red Book, a list of reporting organizations and contact persons is given for a large number of countries [8]. This list indicates that uranium resource data are a compilation of data from the different government agencies, sometimes supplemented by the data from private transnational mining companies. As large national and private interests are involved, the objectivity and the accuracy of the presented data are certainly not assured. Thus, the resource data do not represent the results of an accurate scientific analysis of geological data. Unfortunately, such possible shortcomings of these resource estimates and possible large uncertainties are not mentioned in the Red Book.

However, in absence of better data and in line with the required political consent from many countries, it seems that the editors of the Red Book try to encourage the different countries to provide useful and comparable resource data. As a result, using the US dollar as a universal standard, consistent categories for uranium resources are defined.

Unfortunately, a few comments presented in the Appendix 4 [9] seem to indicate that the Red Book resource data are not as accurate as otherwise stated.

For example it is written that:

- "The categories are defined according to a believed level of confidence." Yet, associated probabilities for the believed existence of the resources are not quantified.
- "The resource categories are defined in terms of the uranium recovery costs at the ore processing plant." However, no explanation on how this cost could have been calculated for "non-existing ore processing plants" in "not yet known environments" is offered. It must

therefore be concluded that such estimates are highly speculative.

- "It is not intended that the cost categories should follow (undefined) fluctuations in market conditions" [10]. This can only mean that cost estimates have been done independently from the mining costs. Not everybody will agree that the increased mining costs of the past few years, related among other things to the energy costs and in particular to the oil price, are just simple "market fluctuations."

In summary, the used methodology leaves some "freedom" on how the correspondents from the different countries should present their resource data. This "freedom" could explain some large RAR resource changes found for different countries from subsequent Red Book editions.

The uranium resources are separated into "conventional" and "non-conventional" resources. The conventional resources are divided into Reasonably Assured Resources (RAR) and the believed-to-exist Inferred Resources (IR). The RAR and IR categories are further subdivided according to the assumed exploitation cost in US dollars. These cost categories are given as < 40 dollars/kg, < 80 dollars/kg, and < 130 dollars/kg.

The non-conventional resources are split into "Undiscovered Resources (UR)," further separated into "Undiscovered Prognosticated Resources (UPR)" with assumed cost ranges of < 80 dollars/kg and < 130 dollars/kg, and "Undiscovered Speculative Resources (USR)." The USR numbers are given for an estimated exploitation cost of < 130 dollars/kg and also for a category with unknown cost.

For the purpose of this analysis, the data from the inclusive "< x dollars/kg" categories are used to calculate the sometimes more informative exclusive resource data with extraction costs between 40-80 dollars/kg and 80-130 dollars/kg.

A critical reader of the Red Book will express doubts about the quality of the data, when only roughly known numbers are given with an unbelievable precision of 0.1% or better. In this respect, it seems to be an ironic mistake that the best known numbers in the RAR categories are given with an accuracy of 1/1000 but the speculative IR and UR categories are presented with an accuracy of 1/10,000, although some progress has been made since the Red Book 2005 edition, when the claimed accuracy was presented with an accuracy of 1 part per million. Names like "Undiscovered Resources" and "Undiscovered Speculative Resources" should leave the reader with serious doubts about the reliability of the claims made concerning the amount of uranium available in these categories in spite of the claimed accuracy.

A more accurate assessment methodology would include effects from changes in uranium mining technology and its related costs, the quality of the mining equipment, the oil price, salaries, and the often ignored huge costs to repair environmental damages following previous uranium exploration. In addition, detailed information should be provided on (1) how variations of the dollar exchange rate have modified the resource data, and (2) how past uranium extractions have been taken into account.

We leave it to the reader to reflect on the question whether the used Red Book methodology results in accurate estimates for the discovered and undiscovered uranium resources.

2.2. The economic-geological hypothesis about uranium resources

According to geological estimates, we know that uranium is not a particularly rare metal. Expressed in the words of the relevant WNA document, we are being informed that [11]:

> "Uranium is a relatively common metal, found in rocks and seawater. Economic concentrations of it are not uncommon."

Table 1 shows uranium or grade concentrations for different minerals in the earth crust and in sea water given in parts per million (ppm).

uranium content of:	concentration [ppm U]	uranium / ton
Very high-grade-ore 20% U (Canada)	200 000 ppm U	200 kg/ton
High-grade-ore 2% U	20 000 ppm U	20 kg/ton
Low -grade-ore 0.1% U	1 000 ppm U	1 kg/ton
Very low -grade-ore* (Namibia) 0.01% U	100 ppm U	0.1 kg/ton
Granite	4-5 ppm U	0.004 kg/ton
Sedimentary Rock	2 ppm U	0.002 kg/ton
Earth continental crust (average)	2.8 ppm U	0.003 kg/ton
Sea water	0.003 ppm U	0.000003 kg/ton

*Table 1: The numbers are taken from the August 2009 version of the WNA information paper "Supply of uranium" [11]. The * in the WNA document is associated with very low grade uranium mining from the Rossing mine in Namibia. The document [11] states: "If uranium is at low levels in rock or sands (certainly less than 1000 ppm), it needs to be in a form which is easily separated for those concentrations to be called 'ore' - that is, implying that the uranium can be recovered economically. This means that it needs to be in a mineral form that can easily be dissolved by sulfuric acid or sodium carbonate leaching."*

It is generally accepted that the producible amount of uranium increases dramatically if ore with a lower concentration of uranium can be economically mined. K.S. Deffeyes and I.D. MacGregor [12] have estimated by generally accepted geological methods that this trend must continue until the average uranium concentration of 2.8 ppm is reached. According to Deffeyes and MacGregor, one may expect that the amount of extractable uranium increases approximately by a factor of 300, if the grade of economically exploitable ore decreases by one order of magnitude. However, they also added the usually ignored statement that:

> No rigorous statistical basis exists for expecting a log-normal distribution. This is just an approximate argument as the enormously complex range of geochemical behavior of uranium and its wide variety of different [chemical] binds [determine] the economic deposit. (The two words placed in brackets were added by the author.)

It is thus important to keep in mind that resource calculations based on the above methods may ignore important factors that limit the amount of eventually extractable uranium. For example, one could imagine that a hypothetical super-rich amount of highly concentrated uranium ore exists a few hundred meters below surface. However, if these rocks are isolated from each other and from any other interesting mineral concentration, it can be safely assumed that sizable amounts of these rocks will never be extracted. Thus, in addition to the average ore concentration, one finds that the amount of uranium available at this concentration, its chemical composition, and its surroundings play all an important role in a potential extraction and the associated energy cost.

A consequence of this hypothesis is that, no matter which growth scenario is being assumed, sufficient uranium resources exist in theory if the extraction cost is allowed to increase. It is usually added that the uranium price has only a negligible effect on the overall production cost of the kWhe. Arguments that, instead of the monetary price, the energy return on energy invested (EROEI) needs to be taken into account are usually dismissed with the comment that current uranium extraction costs are small compared to other production costs, and the very-low grade

Rossing mine in Namibia is often given as a proof that we can still go a long way before the extraction cost will become a determining factor [13].

However, rather than exchanging endless arguments about the limitations of this approach, we propose to use the Red Book uranium resource data base to test the above hypothesis, called in the following the *economic-geological hypothesis*. This can be done fairly easily as the Red Book quantifies the RAR and IR uranium resources according to almost equal and increasing cost intervals of 40 and 50 dollars, respectively. According to this hypothesis, much larger uranium quantities are expected for the higher cost categories.

The economically-extractable-uranium-resources-are-limited hypothesis

An alternative hypothesis assumes that uranium is no different in its use in the energy sector in comparison with any other energy resource. Consequently, the "law of diminishing returns" applies also to uranium, and the economical exploitation and use of uranium can be determined in accordance with the following arguments:

- The usage of uranium starts with the finding and exploitation of the big and high-ore grade uranium deposits.
- Once the "big elephants" have been hunted, one turns to smaller and lower-grade uranium deposits. One tries to keep on going by developing and using better and better technology.
- Eventually, the interesting deposits at the mine become too small and too diluted, and the production is terminated. This moment is reached in a similar way for oil and for uranium, and according to the argument of M. K. Hubbert [14] when he replied to David Nissen of Exxon:

> "[T]here is a different and more fundamental cost that is independent of the monetary price. That is the energy cost of exploration and production. So long as oil is used as a source of energy, when the energy cost of recovering a barrel of oil becomes greater than the energy content of the oil, production will cease no matter what the monetary price may be."

While this hypothesis is theoretically very attractive, it cannot be used easily to make a quantitative test. For example, the energy extraction cost and the total energy cost are rarely given in the required detail. Furthermore, it is essentially impossible to quantify the potential "next round of technological improvements." For example, breakthrough new reactor concepts, based on the fuel breeding concept and including perhaps the use of thorium, and much better (but so far unknown) uranium extraction techniques can always be imagined. Thus, as is the case with the peak oil hypothesis, most people will accept this idea only, once an exact peak date for the nuclear energy can be determined. This, of course, can be done only some time after the final decline has become obvious.

2.3. Evolution of uranium resources according to the Red Book

2.3.1. A consistency check of the NEA press declaration

We now turn to two claims made in the 2007 edition of the Red Book (abbreviated in the following as RB07) and transmitted by their own press declaration to the media [4]:

1. "There is enough uranium known to exist to fuel the world's fleet of nuclear reactors at current consumption rates for at least a century, according to the latest edition of the world reference on uranium published today. Uranium 2007: Resources, Production and Demand, also known as the Red Book, estimates the identified amount of conventional uranium

resources which can be mined for less than USD 130/kg to be about 5.5 million tons, up from the 4.7 million tons reported in 2005."
2. "The currently identified resources are adequate to meet the expansion of nuclear power plants from 372 GWe in 2007 to between 509 GWe (+38%) and 663 GWe (+80%) by 2030."

Let us recalculate the numbers presented to the media. The yearly uranium needs to operate the existing nuclear power plants with the 2009 capacity of 370 GWe are about 65,000 tons. As it is claimed above and quantified in the RB07, the conventional uranium resources of 5.5 million tons are the sum of the RAR (< 130 dollars/kg), given as 3,338,300 tons, and the believed to exist IR (< 130 dollars/kg), given as 2,130,600 tons. Following this logic, a simple division tells us that these 5.5 million tons of uranium resources, at constant usage, are sufficient at best for 85 years or "almost a century" and not for "at least a century"!

Furthermore, a more cautious press declaration would perhaps state that:

> "The well known RAR numbers have remained roughly constant during the past years, and these known resources are sufficient to operate the current world's reactor fleet for about 51 years. However, since the amount of believed-to-exist IR resources has increased by about 700,000 tons, another 34 years can be added if this additional IR uranium can indeed be extracted."

Next, we can ask ourselves how long the conventional uranium resources will last under the conditions of +38% or +80% growth scenarios between 2007 and 2030.

Given these growth assumptions, the yearly natural uranium requirements would be between 90,000 tons/year and 115,000 tons/year by the year 2030.

For simplicity, we may assume that the above increase is to be achieved with an average 23 year growth rate of +1.4%/year and +2.5%/year, respectively. Following this growth model, between 1.76 and 2.02 million tons of uranium will have been used already by the year 2030. By the year 2030, the world reactor fleet will need between 90,000 tons/year and 115,000 tons/year. If one assumes furthermore the unlikely case that nuclear energy will remain constant after 2030, the claimed conventional uranium resources from 2007 could thus fuel the 509 GWe power plants scenario up to the year 2071 and the 663 GWe scenario up to the year 2060. Consequently, one finds that the operating life-span of the reactors built during the years 2020 to 2030 will be limited by the amount of identified fuels and not by the expected 60 year life-time.

These simple examples show that the claims made in the NEA press declaration are not justified by their own data, as documented in RB07.

2.3.2. A 20% increase of conventional uranium resources?

As the reported increase of conventional uranium resources between 2005 and 2007 is relatively large, it might be interesting to learn, where and in which price category the increase has happened. Furthermore, one might be curious to see, how the reduced dollar value and the increased mining costs are reflected in the pseudo-precise resource data, and whether a reduction accounting for the yearly uranium extraction is included for the different countries.

We first present, Tables 2-5, the world total resource estimates for the different categories and their evolution as given in the last 4 Red Book editions from 2001, 2003, 2005, and 2007, respectively [15]. In order to simplify the discussion, the numbers are recalculated such that the uranium amounts for a given cost interval can be compared. Table 2 shows the evolution of the conventional resources since 2001. As one can see, the always highlighted huge increase is essentially only associated with changes in the undiscovered-but-believed-to-exist IR resources. Furthermore, the presented RAR data do not indicate that the yearly uranium extraction of roughly 40,000 tons has been taken into account. Tables 3 and 4 show the corresponding evolutions for the RAR and IR categories, split according to the estimated extraction cost range.

Red Book year	RAR [tons] < 130 dollars/kg	IR [tons] < 130 dollars/kg	conventional resources [tons] < 130 dollars/kg
2001	2853000	1080000	3933000
2003	3169238	1419450	4588688
2005	3296689	1446164	4742353
2007	3338300	2130600	5468800

Table 2: Evolution of the conventional uranium resources split into the reasonably assured resource (RAR) and the inferred resource (IR) categories from the latest four Red Book editions. Especially remarkable is the fact that the RAR numbers have increased by only a small amount and remained essentially unchanged since 2003. Hence the claimed large increase in conventional uranium resources since 2001 and especially during the past 4 years is only based on an increase in the IR numbers.

Red Book year	RAR [tons] < 40 dollars/kg	RAR [tons] 40-80 dollars/kg	RAR [tons] 80-130 dollars/kg
2001	1534100	556650	589770
2003	1730495	575197	661941
2005	1947383	695960	653346
2007	1766400	831600	740300

Table 3: Evolution of the reasonably assured resource (RAR) category from the latest four Red Book editions. Especially remarkable is that the highest uranium numbers are found in the lowest cost category and this category has, after regular large increases, suddenly decreased since 2005 by about 180,000 tons.

The RAR numbers, even though claimed to be known with incredible precision, fluctuate by a large amount. The drop of 180,000 tons in the cheapest and best understood < 40 dollars/kg category between 2005 and 2007 is remarkable, and more details about this reduction will be given in Section 3.

Ups and downs of up to ±10% may appear reasonable. For example, one might expect that inflation moves some resources from a cheaper to a more expensive category. Such an explanation, however, would also require that a certain amount be moved out of the highest cost category into a yet more expensive category.

Next we turn to more speculative uranium resources. In Table 4, the not-yet-found-but-believed-to-exist IR uranium data are presented. Especially suspicious is the large increase of 400,000 tons in the < 40 dollars/kg IR category. This increase can be compared with the corresponding RAR numbers from Table 3, which decreased during the same period by 180,000 tons.

The situation becomes even more suspicious when one compares the evolution of the IR category during the past six years from 2001 to 2007. For example, the < 40 dollars/kg IR category increased by a factor of 2.2, and the 40-80 dollars/kg category increased by a factor of 3.5. In comparison, the amount in the 80-130 dollars/kg category changed by only a factor of 1.3. Finally, one can compare the evolution of the conventional resources in the RAR category and the more speculative IR category. As mentioned already, large exploration efforts during the past years have left the total RAR numbers essentially unchanged but have increased the believed-to-exist IR figure by a large amount. This means that the claimed increase from 2005 to 2007 in the conventional uranium resources is not based on real discoveries, but on an unexplained hope factor associated with the IR deposits that remain to possibly be discovered.

More details about these changes will be discussed in the individual country analysis below.

Red Book year	IR [tons] less than 40 dollars/kg	IR [tons] 40-80 dollars/kg	IR [tons] 80-130 dollars/kg
2001	552000	186950	225150
2003	792782	275170	320868
2005	798997	362041	285126
2007	1203600	655480	272200

Table 4: Evolution of the not-yet-discovered-but-believed-to-exist IR uranium resources as given in the last four editions of the Red Book. Remarkable is the claim that the cheaper cost categories increased by a large amount, whereas the highest cost category has even decreased.

Table 5 shows the evolution of the undiscovered prognosticated and speculative UPR and USR resource categories. In contrast to the increase from 2003 to 2007 in the conventional IR resources, only relatively minor changes are claimed for the even more uncertain UPR and USR resources.

Red Book year	UPR [tons] less than 80 dollars/kg	UPR [tons] 80-130 dollars/kg	USR [tons] less than 130 dollars/kg
2001	1480000	852000	4438000
2003	1474600	779900	4437300
2005	1700100	818700	4557300
2007	1946200	822800	4797800

Table 5: Evolution of the undiscovered prognosticated UPR and speculative USR uranium resources according to the past four Red Book editions. In comparison to the large relative changes in the IR data, the numbers presented show a surprising stability.

One finds from Tables 3-5 that the uranium resources in the RAR, IR, and UPR categories decrease for the higher cost intervals. Furthermore, one observes that the estimated world RAR, IR, and UPR numbers have changed in peculiar and unnatural ways.

Consequently, the overall uranium resource data and their evolution are in contradiction with the economic-geological hypothesis presented in Section 2.2.

Furthermore, with inflation effects being ignored, one would expect that the changes of the uranium quantities in the RAR, IR, and UPR categories should follow similar patterns. As the uranium resource data do not confirm such expectations, one is left with the conclusion that the true quality of the presented uranium data is considerably poorer than claimed by the Red Book.

3. Evolution of uranium resources in selected countries

In order to understand how and where uranium resources have changed during the past few years, one needs to study the information provided by the correspondents from a few different countries with large resources. To this end, the Red Book editions from the years 2003 (RB03), 2005 (RB05), and 2007 (RB07) will be used. We restrict the discussion to those 10 countries that claim to have more than 100,000 tons of extractable RAR uranium resources for < 130 dollars/kg within their territory. Combined, these 10 countries cover a surface area of about 52 million km^2 or more than 1/3 of the total land area of our planet. After at least 50 years of non-negligible world-wide geological research efforts, these countries claim to have 80% of the remaining known world uranium resources and up to 95% of the uranium in the economically most interesting < 40 dollars/kg RAR category. Roughly 90% of the total uranium extraction in 2007 came from these 10 countries.

Tables 6 and 7 show the claimed amount of RAR uranium resources for these countries in the < 40 dollars/kg and 40-130 dollars/kg categories.

country	RAR (RB03) 40 dollars/kg [tons]	RAR (RB05) 40 dollars/kg [tons]	RAR (RB07) 40 dollars/kg [tons]
Australia	689000	701000	709000
Brazil	26235	139900	139600
Canada	297264	287200	270100
Kazakhstan	280620	278840	235500
Namibia	57262	62186	56000
Niger	89800	172866	21300
Russia	52610	57530	47500
South Africa	119184	88548	114900
Ukraine	15380	28005	27400
USA*	102000	102000	99000
sum	1627000	1714000	1621000

Table 6: Evolution of the lowest-cost RAR uranium category for the 10 countries claiming to have a total of more than 100,000 tons of RAR resources on their territory. An especially remarkable change during the years 2005 to 2007 can be seen for Niger. (The USA report does not offer a number for the < 40 dollars/kg RAR category. For this reason, the amount claimed in the < 80 dollars/kg has been used here.)*

Some spectacular ups and downs can be observed for the three Red Book editions. For example between 2005 and 2007, the RAR reserves in the < 40 dollars/kg category decreased by 15% (minus 40,000 tons) for Kazakhstan and by 88% (minus 150,000 tons) for Niger. Drastic changes during these two years are also reported in the 40-130 dollars/kg RAR category for Australia, Kazakhstan, Niger, Russia, and the Ukraine. Despite the fact that the RAR numbers, especially in the < 40 dollars/kg category, are assumed to present the most accurate estimate, no explanations for the often dramatic changes are offered.

country	RAR (RB03) 40-130 dollars/kg [tons]	RAR (RB05) 40-130 dollars/kg [tons]	RAR (RB07) 40-130 dollars/kg [tons]
Australia	46000	46000	16000
Brazil	59955	17800	17800
Canada	36570	58000	59100
Kazakhstan	249840	235057	142600
Namibia	113270	120370	120000
Niger	12427	7600	222180
Russia	90410	74220	124900
South Africa	196146	167045	169500
Ukraine	49280	38701	107600
USA*	345000	342000	339000
sum	1198900	1106800	1318700

Table 7: Evolution of the higher-cost RAR uranium category for the 10 countries claiming to have a total of more than 100,000 tons of RAR resources on their territory. Especially remarkable are the changes from 2005 to 2007 for Australia, Kazakhstan, Niger, Russia, and the Ukraine. A comparison of these changes with the ones in the low-cost category presented in Table 6 is also interesting. (As the USA does not report the < 40 dollars/kg RAR category separately, the amount in the 80-130 dollars/kg category has been used here.)*

The changes for the yet unobserved-but-believed-to-exist IR resources offer even more interesting insights. As presented in Section 2, and in contrast to the essentially unchanged claimed total RAR resources, the data reported for the IR category at the < 130 dollars/kg price tag have increased by almost 700,000 tons between the years 2005 and 2007. Spectacular and unlikely relative changes for some countries can be observed from Table 8, where we present ratios of the resource numbers found presented in RB07 and RB05 for two IR cost categories and for the UPR category. An especially remarkable increase is observed for Russia. It is claimed that their IR 40-130 dollars/kg category increased by a factor of 17.7 from 19,000 tons to 337,000 tons. The reported changes of the IR data for Australia, Kazakhstan, Niger, and the Ukraine are also interesting.

country	ratio (RB07/RB05) IR < 40 dollar/kg [%]	ratio (RB07/RB05) IR 40-130 dollar/kg [%]	ratio RB07/RB05 UPR < 130 dollar/kg [%]
Australia	1.42	0.48	NA
Brazil	1	1	1
Canada	0.97	0.83	1
Kazakhstan	2.18	0.91	0.97
Namibia	0.99	0.99	NA
Niger	NA	0.4	1
Russia	1.67	17.7	2.65
South Africa	2.19	1.01	1
Ukraine	1.03	3.5	1.47
USA	NA	NA	1
world total	1.5	1.43	1.1

Table 8: The IR resource ratios as obtained from the Red Book 2007 and 2005 editions for the 10 countries claiming to have a total of more than 100,000 tons of RAR resources on their territory. Not all countries have submitted or updated these numbers for the 2007 edition. Especially remarkable changes are observed for Russia, where the category IR (40-130 dollars/kg) is now estimated to be 337,000 tons. Changes for Australia, Kazakhstan, Niger, and the Ukraine are also interesting.

As we have seen already in Section 2, the celebrated increase of the conventional uranium resources does not come from new discoveries of interesting uranium deposits, but from a new evaluation of the supposed-to-exist IR resources. This statement can now be made more quantitatively. The data show that this claimed increase of the IR resources comes essentially only from Russia (from 40,652 tons to 373,300 tons), Australia (from 396,000 tons to 518,000 tons), Kazakhstan (from 302,202 tons to 439,200 tons), and the Ukraine (from 23,130 tons to 64,500 tons).

A closer look at Russia shows that this increase is highly suspicious. Whereas the IR number in the < 40 dollars/kg category changed by only 15,000 tons from 21,572 tons to 36,100 tons, an incredible increase from 19,080 tons to 337,200 tons is presented for the 40-130 dollars/kg category.

Kazakhstan is another example of a country with drastic changes of its IR data. From the RB05 and RB07, one finds that the IR number for Kazakhstan in the < 40 dollars/kg category increased from 129,252 tons in the 2005 estimate to 281,800 tons in 2007, whereas the 40-130 dollars/kg number decreased from 172,950 to 157,400 tons. The very speculative UPR and UPS data for Kazakhstan remained essentially unchanged.

As discussed in Parts I and II of this report [6], the evolution of uranium mining in Kazakhstan is of particular importance to avoid a world uranium supply shortage during the coming 5-10 years. It is claimed that, provided enough investments in the mining sector are done, this country can triple its uranium extraction within the next 10-15 years from 6637 tons in 2007 to 21,000 tons in 2015. A high estimate for future uranium discoveries in the low-cost category certainly helps to raise foreign interest in investments in the Kazakh uranium mining infrastructure.

Australia and South Africa also claim large increases, but their resources increased only in the < 40 dollars/kg IR category. In contrast, the IR data for Canada, Brazil, and the USA remained unchanged at their 2005 values.

The above examples demonstrate that a large percentage of the claimed uranium resources and their evolution are not backed up by geological methods.

3.1. Are some uranium resource data not based on geological methods?

If one accepts that uranium resource data for some countries are not based on geological methods, it follows that other methods have helped to fill the tables of the Red Book.

Consequently and in absence of explanations, one is somehow invited to formulate ideas about why some particular countries, probably with the help from large mining companies, might be interested in presenting either too high or too low resource numbers.

For example, one can imagine that "sudden" increases in resource numbers, as observed for Aus tralia, Kazakhstan, Russia, and South Africa, will help to attract foreign investments.

In contrast, a sudden and drastic reduction in the most interesting < 40 dollars/kg RAR category, as observed for Niger, could be motivated by wishes to (1) keep potential uranium mining competitors out of the country, or (2) prevent the government and the people of a country to become informed about the exact wealth of a mining company that wants to either reduce its tax burden in this way or dissuade the government from expropriating it.

3.2. Relations between different cost categories

We now compare the individual country resource data with the economic-geological hypothesis presented in Section 2.2. Starting with the lowest and highest RAR and IR cost categories of < 40 dollars/kg and 80-130 dollars/kg, one finds that some country estimates show surprisingly large differences in these categories with respect to the world average. For example, 53% of the world RAR resources are expected in the < 40 dollars/kg categories, but only 22% are expected in the 80-130 dollars/kg category, which is in strong disagreement with the economic-geological hypothesis.

The disagreement with this hypothesis becomes even stronger for Australia, Canada, and Kazakhstan. Australia claims 98% of the RAR to be in the low-cost category. Too high numbers for this category are also reported from Canada (82%) and Kazakhstan (62%).

In contrast, the numbers in this cost category for Russia (28%) and Niger (9%) are very low. For Niger, the uranium amount in this class is now given as 21,300 tons, which is about 150,000 tons smaller than the amount claimed in the 2005 edition, when 96% of the country's RAR resources were assigned to the < 40 dollars/kg category.

The data reported for the IR category show similar discrepancies between the world average ratios and the ones from individual countries. One finds that world-wide, 56% of the IR resources are predicted in the < 40 dollars/kg, whereas 13% are predicted in the 80-130 dollars/kg categories. In comparison, the correspondents from Australia, Canada, and Kazakhstan think that 94%, 88%, and 64%, respectively will be found in the < 40 dollars/kg category. The three countries thus predict that their not-yet-discovered IR resource fractions match almost perfectly the corresponding RAR fractions.

In contrast, the correspondents from Russia assume that only 9.7% of their IR resources will eventually be found in the low-cost category. For Niger, the low-cost IR fraction is given as 42%, and is thus close to the world average.

The Red Book uranium resource data show that the economic-geological hypothesis is not backed up by the data. This conclusion is strengthened beyond any doubt, if one believes that Australia and Canada provide the most reliable resource data.

The relation between the RAR numbers and the IR numbers is also interesting. For the < 40 dollars/kg category, Australia assumes to know about 709,000 tons RAR and expects to find another 487, 000 tons in the IR category, or 69% of the RAR number. In contrast for Canada, the RAR number is given as 270,000 tons and the IR number is presented as 82,000 tons, thus only 30% of the RAR number.

3.3. Uranium mining and its effect on resource data

Finally, we would like to see how uranium extraction, claimed to be known accurately to the ton, e.g. far better than with a 0.1% accuracy, influences the remaining amount of uranium in the different RAR resource categories and in some selected countries.

For this investigation, we remind the reader that world-wide about 40,000 tons of uranium are mined on average every year. For many years and despite non-negligible efforts made by many countries, only three countries extract about 60% of this uranium and individually more than 5000 tons per year. Another 25% of this uranium come from three countries that contribute about 3000 tons/year each, and further 12% stem from three additional countries that together extract roughly 5000 tons/year.

Furthermore, the uranium extraction is concentrated in the hands of a few transnational mining companies. The four biggest among them: Rio Tinto, Cameco, Areva, and KazAtomProm provided about 26,000 tons/year to the world uranium market, about 59% in 2008. Despite the claim that plenty of cheaply extractable uranium can be found almost everywhere on the planet and that the extraction cost does not play a significant role, 66% of the 41,000 tons extracted in 2007 came from only 10 uranium mines.

The biggest mine today, McArthur River in Canada owned dominantly by Cameco, extracted 7200 tons of uranium in 2007, or about 18% of the world-wide production.

This number might be compared with today's stressed world oil situation, where the largest oil field ever, Ghawar in Saudi Arabia, contributes about 6% of the total world oil production. It might thus be more accurate to compare the fraction of uranium production from this one mine alone with the fraction of oil produced by Saudi Arabia and Kuwait combined.

The mine started only about 10 years ago and reached 7200 tons/year during the years 2002-2007. Since the startup in the year 2000, about 58,000 tons have been extracted. According to Cameco, this mine exploits the world largest high-grade uranium deposit with proven and probable reserves of 332.6 million pounds of U3O8. This corresponds to an equivalent of 130,000 tons of natural uranium, with about 65,000 tons assigned to the proven reserves as of December 31, 2008 [17]. This mine seems to be past its peak by now, as in 2008, only 6383 tons were produced, and the output of the first half of 2009 reported by Cameco on August 12, 2009, appears to again be 12% lower than the one obtained during the same period in 2008 [18]. If one assumes that about 50% of the economically extractable uranium had been mined up to 2005/06, the presumed peak year, one could estimate that, instead of the 65,000 tons claimed, only about 45,000 to 50,000 tons remain to be mined. The next few years will tell, if the decline rate observed since 2007 will continue.

The next two mines, Ranger in Australia and Rossing in Namibia, produced together 8000 tons of uranium in 2008, about 25% more than the McArthur River mine alone. Combined, the three largest mines produced 33% of the total and slightly more than the next 7 big uranium mines together. This fraction corresponds roughly to the entire OPEC share of the world oil production.

Thus, uranium extraction is much more centralized and monopolized than any other energy resource. In fact, if the world oil situation, with a few giant oil companies and a country cartel, frightens policy makers and most oil consumers, the uranium situation is by all standards even more dangerous.

We shall now analyze whether the amount of uranium extracted during the past years has some effect on the RAR numbers. For this study, we use the uranium quantities extracted during the past few years as provided in the different editions of the Red Book and summarized in a single table in a WNA information paper [16].

Starting with the largest producer country, Canada, one finds that the three large existing mines extracted essentially 100% of the 9477 tons and 9000 tons in 2007 and 2008, respectively. During the years 2003-2004 and 2005-2006, the total extracted uranium is given as 22,055 tons and 21,491 tons, respectively. Table 6 shows that the < 40 dollars/kg RAR category decreased during these two year periods by 10,064 tons and 17,100 tons, respectively. As it seems reasonable to assume that the existing big uranium mines operate and deplete only the < 40 dollars/kg category currently, the numbers show that only 50% (2005) and 80% (2007) of the decrease can be accounted for directly. Two explanations are possible, (1) about 12,000 tons (2003+2004) and 4000 tons (2005+2006) of new deposit in the < 40 dollars/kg RAR category have been discovered during the considered two-year periods, or (2) the extraction figures are not adequately taken into account.

We now turn to Australia, the second-largest contributor of uranium. During the four years from 2003 to 2006, a total uranium extraction of 33,663 tons is reported, while the < 40 dollars/kg category increased by 20,000 tons in accordance with Table 6. As Australia does not claim to have significant amounts of uranium in the 40-80 dollars/kg and 80-130 dollars/kg RAR categories, one concludes again that essentially all of the extracted uranium came from the < 40 dollars/kg RAR category. Consequently, the new findings in this category from 2003 to 2006 must have been about 54,000 tons. However, such large new uranium discoveries over a four-year period are puzzling as the other two RAR cost categories of 40-80 dollars/kg and 80-130 dollars/kg remained unchanged between 2003 and 2005 and even decreased by 8000 tons and 22,000 tons between 2005 and 2007. Thus, the extraction numbers from Australia are clearly inconsistent with the reported RAR numbers.

As a last example, we analyze the situation in Niger, a former French colony, that became indepen dent in 1960. It is one of the poorest countries in the world with an electricity production of roughly 0.234 billion kWh (2005), corresponding to an almost negligible amount of 18 kWh per year and per person. Yet, the 3032 tons of uranium extracted in 2008 allowed to fuel almost 20 GWe of nuclear power plants in France and other European countries, which produced roughly 140 billion kWh during that year. Between 2003 and 2006, about 13,000 tons of uranium have been extracted from the mines operated dominantly by Areva, a French transnational nuclear company.

In 2003, the RAR resources were reported as 89,800 tons in the < 40 dollars/kg and 12,447 tons in the 40-130 dollars/kg category. These numbers changed in 2005 by incredible amounts to 172,866 tons and 7600 tons, respectively. Another drastic change is reported in the 2007 Red Book, where the corresponding RAR numbers are now given as 21,300 tons and 222,180 tons, respectively.

Clearly, the 13,000 tons of uranium extracted during these 4 years are not accounted for, and the Red Book authors do not care to comment about the incredibly large jumps back and forth between the < 40 dollars/kg and 40-130 dollars/kg RAR categories.

These numbers must contain a substantial fantasy factor, which can perhaps be explained with the misinformation hypothesis. This suspicion is further supported by Areva's problems with the real owners of the mines, often referred to as "Tuareg rebels," who (somewhat understandably) ask for a larger share in the profits.

In summary, the claimed "high-precision" uranium resource data and the known extraction data from the past few years do not match up. These and the other inconsistencies described in Sections 2 and 3 of this article raise suspicions about the reliability of the RAR uranium data.

4. Consequences for the long-term nuclear energy future

The analysis presented in Sections 2 and 3 of this article demonstrates that the uranium resource data, prepared, updated, and published every two years by the IAEA and the NEA in the Red Book, do not measure up to the claimed high-precision standards. On the contrary, it even seems that some individual country resource data are not based on a scientific geological resource estimate.

Consequently, fairly large error margins should be associated even with the reasonably assured resources (RAR) category. As an example, one could assume the RAR resource numbers reported by Australia and Canada, who claim almost all of their RAR resources in the low-cost category, to be most reliable. If this idea is applied to the entire world, one would guess that only the numbers in the < 40 dollars/kg RAR category are reliable and therefore relevant. As a result, the known uranium resources could be guessed as ≤ 2 million tons, corresponding to a resource life-time of just 30 years at the current consumption rate.

Such an evaluation would certainly discourage the idea of constructing new standard light water reactors with a presumed life-time of 60 years.

This simple-minded example demonstrates that more realistic uranium resource information is urgently needed. Such an analysis, clearly beyond the scope of this paper, would have to be based on a critical mine-by-mine and country-by-country analysis.

At the current time, however, the Red Book uranium resource data are the only existing and usable data base. These data, including large uncertainties, demonstrate that the economic-geological hypothesis is contradicted by the data. This widely used hypothesis states that more and more uranium can be extracted if only the price is allowed to increase. This claim is in total disagreement with the overall resource data and with the data offered by many individual countries.

Thus, one is left with the choice of either rejecting the Red Book data completely and sticking with an unproven hypothesis, or giving up that unproven hypothesis.

In summary, we point out that countries interested in the construction of a new nuclear power plant within the next 10-20 years should find a way to guarantee their needed uranium fuel for at least 40 years, before they invest perhaps up to 4 billion Euro per GWe of installed power.

The warning applies to all Western European countries, Japan, and South-Korea, which depend to almost 100% on stable uranium deliveries from far away. These countries should take one particular paragraph from the Red Book 2007 NEA press declaration very seriously:

> "At the end of 2006, world uranium production (39,603 tons) provided about 60% of world reactor requirements (66,500 tons) for the 435 commercial nuclear reactors in operation. The gap between production and requirements was made up by secondary sources draw down from government and commercial inventories (such as the dismantling of over 12,000 nuclear warheads and the re-enrichment of uranium tails). Most secondary resources are now in decline and the gap will increasingly need to be closed by new production. Given the long lead time typically required to bring new resources into production, uranium supply shortfalls could develop if production facilities are not implemented in a timely manner."

Many other reports have studied the world uranium supply situation in detail. Even though most of these reports assume, contrary to our study, that the Red Book uranium resource data are largely correct, very similar conclusions about the short- and long-term critical uranium supply situation are reached. The list below provides references to some recent studies that reach the conclusion that the known uranium deposits and techniques of uranium extraction are not sufficient to fuel a nuclear energy renaissance based on conventional light water reactors.

The following three studies are from groups that favor nuclear energy. They find that even a small 1% annual nuclear power growth scenario will be faced with serious and unsolved uranium supply problems during the first half of the 21st century.

- A report published in 2002 entitled: *A Technological Roadmap for Generation IV Nuclear Energy Systems* [19] points out that the known conventional uranium resources will only last between 30-50 years. Thus, a new conventional nuclear power plant, which might be operational in 2020, may only obtain uranium fuel until sometime between 2040 and 2050.
- The authors of an IAEA 2001 report entitled *Analysis of Uranium Supply to 2050* [20] quantify the uranium deficit with respect to the RAR numbers for different scenarios about the future use of nuclear fission energy. The estimated deficit is given in units of millions of tons of uranium. Many details about the potential contributions of uranium from a large number of unconventional resources are presented in that report (Section 5), and especially the remarks about sea water uranium are remarkable: "Research on extracting uranium from sea water will undoubtedly continue, but at the current costs sea water as a potential commercial source of uranium is little more than a curiosity."
- A 2007 M.I.T. study group concluded that "lack of fuel may limit U.S. nuclear power expan sion" [21].

Other groups of analysts with critical views concerning nuclear fission energy have also studied the Red Book uranium resource data. All these studies, even if they assume that the Red Book uranium resource numbers are more or less accurate, conclude that a substantial increase of nuclear fission energy, using conventional light water reactors, is essentially impossible.

- The *Energy Watch Group* report of December 2006 [22] with Dr. Werner Zittel and Jörg Schindler of the Ludwig Bölkow Systemtechnik GmbH as the principle authors conclude that: "If only 42,000 tons/year of the proved reserves below 40 dollar/kg can be converted into production volumes, then supply problems are likely even before 2020. If all estimated known resources up to 130 dollar/kg extraction cost can be converted into production volumes, a shortage can at best be delayed until about 2050."
- The WISE Uranium Project *Uranium Supply and Demand* [23] contains some interesting graphics that relate the various resource categories from the 2005 Red Book with some modest nuclear growth scenarios and demonstrate the year when the uranium supply cliff will be reached.
- In the article *The Red Face Book* published by Sanders Research in September 2008, John Busby analyzed the 2007 Red Book in much detail [24]. Many of the internal inconsistencies of the Red Book 2007 have most likely been pointed out in this article for the very first time. His presented conclusions about the near- and long-term uranium supply troubles are essentially identical to the ones obtained independently and with a somewhat different approach in the first three parts of this four-part article [6].
- Another important report published in November 2007, *The Lean Guide to Nuclear Energy*, by David Fleming [25] has focused on many issues of nuclear energy and their inconsistencies. Fleming concludes his discussion with the statement: "Shortages of uranium and the lack of realistic alternatives leading to interruptions in supply, can be expected to start in the middle years of the decade 2010-2019, and to deepen thereafter."
- Finally we would like to reference the report *Nuclear Power - The Energy Balance* by Jan Willem Storm van Leeuwen and Philip Smith and its latest update by Jan Willem Storm van Leeuwen [26]. This report offers, among other things, an energy balance of the entire nuclear power chain, starting from the mining to the waste disposal. It presents the hypothesis that "economically extractable uranium resources are limited."

5. Summary

Despite the shortcomings of the Red Book and its associated large uncertainties, some valuable information can still be extracted from it. Perhaps the most important results of our analysis are:

- The "economic-geological hypothesis" that more uranium resources can be extracted if only one is willing to pay a higher price is in direct contradiction with the Red Book resource data.
- Realistic uranium resource data cannot be obtained directly from the Red Book. However, a detailed comparison of the data from current and past editions of the Red Book and the often far too drastic resource changes reported, following some observations from this analysis, can possibly be used in the future to obtain better resource estimates.
- The economically extractable uranium resources in many countries are most likely much smaller than generally believed. In absence of a Red Book document that measures up to its claims, only the RAR uranium data in the < 40 dollars/kg category are reliable and believable.

The analysis presented in this and the previous two parts of this four-part article [6] demonstrates that the current uranium extraction and the believed-to-exist uranium resources are incompatible with even a modest growth scenario of conventional nuclear fission power.

A debate about the future of nuclear energy must therefore be based on the two questions:

1. When – if ever – will reliable and safe commercial breeder reactors based on uranium or

thorium become available? and
2. Will nuclear fusion power be always 50 years away?

The current situation and the prospects about these future hypothetical options will be presented in the fourth and final part of this report.

Our analysis can thus best be summarized with an addition to the recent warning from Fatih Birol, the chief economist of the International Energy Agency [27]: "We should leave oil before it leaves us," by stating that "we should also terminate the use of nuclear fission energy based on standard light water reactors before uranium leaves us as well."

References

[1] Cf. for example the *Joint Oil Data Initiative* available at http://www.jodidata.org/ and the related G8 declaration *Responsible Leadership for a Sustainable Future* presented at the G8 Summit 2009, 8 -10 July 2009, in L'Aquila, Italy, available at http://www.jodidata.org/WS_23.htm.

[2] The 2006 review *Forty Years of Uranium Resources, Production and Demand in Perspective. The Red Book Retrospective* can be found at the OECD bookshop http://www.oecdbookshop.org/oecd/display.asp?K=5L9N4JNZGN0W&LANG=EN. A free online version can be found via Google books.

[3] The detailed numbers are extracted from the Red Book 2007 edition, *Uranium 2007 Resources, Production and Demand*. The book is published every two years by the IAEA/NEA and can be found at the OECD book store http://www.oecdbookshop.org/oecd/display.asp?K=5KZLLSXQS6ZV&DS=Uranium-2007. Free online versions of some past editions can be found via "Google books."

[4] Nuclear Energy Agency press declaration of June 3, 2008 concerning the 2007 edition of the Red Book: *Uranium 2007 Resources, Production and Demand* to be found at http://www.nea.fr/html/general/press/2008/2008-02.html.

[5] Cf. for example the presentation *Long-Term Sustainability of Nuclear Fission Energy* by Byron Little presented at the 2006 American Nuclear Society Meeting http://www.sustainablenuclear.org/PADs/pad0606little.pdf. Other examples of the Red Book data use are reported at http://www.inea.org.br/UraniumavailabilityINEAr1.pdf and http://www.wise-uranium.org/uod.html.

[6] Parts I and II of this four-part article have been published at the Oil Drum, August 2009 at http://europe.theoildrum.com/node/5631 and http://europe.theoildrum.com/node/5677, respec tively. The articles are also available at the preprint archive http://xxx.lanl.gov/ filed under *Physics and Society* at http://xxx.lanl.gov/abs/0908.0627 and http://xxx.lanl.gov/abs/0908.3075, respectively.

[7] Cf. reference [3], page 3 (Preface).

[8] Cf. reference [3], pages 383-385 (Appendix 2).

[9] Cf. reference [3], pages 391f (Appendix 4).

[10] Cf. reference [3], page 393 (Appendix 4).

[11] The numbers and the quote are taken from the WNA document *Supply of Uranium* to be found at http://www.world-nuclear.org/info/inf75.html.

[12] For more details cf. http://en.wikipedia.org/wiki/Uranium_depletion and the reference to

the publication by K.S. Deffeyes, and I.D. MacGregor at http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=6665051.

[13] For more information from Rio Tinto about the Rossing mine cf. http://www.rossing.com/. Additional information can be found at http://en.wikipedia.org/wiki/Rossing_Uranium_Mine.

[14] Dr. Hubbert (in response to remarks by David Nissen - Exxon) http://www.oilcrisis.com/Hubbert/to_Nissen.htm.

[15] The numbers are extracted from the Red Book 2001, 2003, 2005, and 2007 editions: *Ura nium Resources, Production and Demand*. The books can be found at the OECD bookshop http://www.oecdbookshop.org/oecd/index.asp?lang=en. Free online versions of some past editions can be found via "Google books."

[16] The data are obtained from the WNA information paper *World Uranium Mining* to be found at http://www.world-nuclear.org/info/inf23.html.

[17] For details about the McArthur River mine cf. the Cameco report at http://www.cameco.com/mining/mcarthur_river/ and the WNA information paper: *Uranium Production in Canada* at http://www.world-nuclear.org/info/inf49.html.

[18] Detailed reports from Cameco can be found in the report: *Second Quarter Earnings* at http://www.cameco.com/media/news_releases/2009/?id=488.

[19] Cf. the *Generation IV Technology Roadmap* and the latest evolution at http://gif.inel.gov/roadmap/. The uranium resource problem is presented on page 13 of the roadmap document http://gif.inel.gov/roadmap/pdfs/gen_iv_roadmap.pdf.

[20] The year 2001 IAEA report: *Analysis of Uranium Supply to 2050* can be found at http://www-pub.iaea.org/MTCD/publications/PDF/Pub1104_scr.pdf.

[21] A summary of the MIT study and further links can be found at http://web.mit.edu/newsoffice/2007/fuel-supply.html.

[22] The report from the energy watch group can be found at http://www.energywatchgroup.org/fileadmin/global/pdf/EWG_Report_Uranium_3-12-2006ms.pdf.

[23] The slides can be found at http://www.wise-uranium.org/stk.html?src=stkd03e.

[24] The Report by John Busby can be found at http://www.after-oil.co.uk/redfacebook.htm.

[25] The report by Dr. Fleming can be found at http://www.theleaneconomyconnection.net/downloads.html#Nuclear.

[26] The detailed report and some corresponding discussions with critiques by J.W. Storm can be found at http://www.stormsmith.nl/.

[27] This quote from F. Birol can be found for example at http://www.independent.co.uk/news/science/warning-oil-supplies-are-running-out-fast%C2%AD1766585.html.