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The End of Cheap Uranium

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Abstract

Historic data from many countries demonstrate that on average no more than 50-70% of the uranium in a deposit could be mined. An analysis of more recent data from Canada and Australia leads to a mining model with an average deposit extraction lifetime of 10 ± 2 years. This simple model provides an accurate description of the extractable amount of uranium for the recent mining operations.

Using this model for all larger existing and planned uranium mines up to 2030, a global uranium mining peak of at most 58 ± 4 ktons around the year 2015 is obtained. Thereafter we predict that uranium mine production will decline to at most 54 ± 5 ktons by 2025 and, with the decline steepening, to at most 41 ± 5 ktons around 2030. This amount will not be sufficient to fuel the existing and planned nuclear power plants during the next 10-20 years. In fact, we find that it will be difficult to avoid supply shortages even under a slow 1%/year worldwide nuclear energy phase-out scenario up to 2025. We thus suggest that a worldwide nuclear energy phase-out is in order.

If such a slow global phase-out is not voluntarily effected, the end of the present **cheap uranium** supply situation will be unavoidable. The result will be that some countries will simply be unable to afford sufficient uranium fuel at that point, which implies involuntary and perhaps chaotic nuclear phase-outs in those countries involving brownouts, blackouts, and worse.

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1 Introduction

Nuclear fission energy in industrial societies is often proposed as a long term replacement for the limited fossil fuel resources and as a solution to the environmental problems related to their use. However, even 50 years after commercial nuclear fission power began, nuclear reactors produce less than 14% of the world's electric energy, which itself makes only about 16% of our final energy demand [1]. More than 80% of the 440 nuclear power plants, with a capacity of 374 GWe [2], are operated in the richer OECD countries, where they produce about 21% of the annual electric energy [1]. The relatively small nuclear energy contribution today indicates that even a minor transition from fossil to nuclear fuel for generating electric energy over the next 20 to 30 years would require significant increases in the use of nuclear fuel.

During the last few years a "nuclear energy renaissance" strategy was discussed in many countries. However, after the 2011 Fukushima disaster, the enthusiasm to build new reactors has slowed down in most countries and even the planning for some replacement strategies for the aging existing nuclear power plant in most OECD countries has been brought essentially to a standstill. From the 68 reactors currently under construction in 14 countries, one finds that 46 of them are build in just three countries –China, India and Russia [2]. As a result, even the Word Nuclear Association (WNA) can imagine at most a worldwide nuclear growth scenario of 1-2%/year during the next 10-15 years [3]. Among the many problems related with this small growth scenario is the little discussed but fundamental issue of uranium fuel supply [4].

In this paper we present our findings about the future uranium supply. Our results are obtained from a study of deposit depletion profiles from past and present uranium mining. Our analysis shows that the existing and planned uranium mines up to 2030 allow at most an increase of the uranium supply from 54 ktons (54 000 tons) in 2010 [5] to 58 ± 4 ktons in 2015. Furthermore, the data indicate that after 2015 production will decline by at least 0.5 ktons/year. The annual uranium supply around 2025 and 2030 is thus predicted to reach at most 54 ± 5 ktons and 41 ± 5 ktons respectively. These numbers are not even anywhere near the *present* global usage, about 68 ktons/year, and imply significant shortages over coming decades. We thus predict an end of the current situation of cheap uranium and a voluntary or forced worldwide nuclear phase-out scenario. It is in fact roughly consistent with the new policies, following the Fukushima accident, proposed in May 2011 by the governments in Germany and Switzerland.

We start our analysis with countries where uranium mining was stopped or reduced to about 10% of the past production levels because of depletion (Section 2). The more accurate recent mining data from Canada and Australia are used to formulate a simple and accurate mining and depletion model (Section 3). In Section 4 this model is applied to the currently operating and planned future uranium mines up to 2030.

2 Lessons from past uranium mining and depletion

Significant uranium extraction started after the Second World War [6, 7]. Including the year 2010, a total of about 2.5 millions tons of uranium have been mined and about 2 million tons have been used for electric energy production. Most of the remaining 500 ktons are essentially under the control of the military in Russia and the USA.

Uranium mining between 1945 and 2005 can be divided into three periods. The first period (1945-1975) can be associated with the rush to fulfill the military uranium requirements during the nuclear arms race. An extraction peak of almost 50 ktons/year was achieved around the year 1959, after which mining declined to about 35 ktons/year between 1965-1975. About 750 ktons of uranium were extracted during that period.

The second period (1975-1990) coincided with the time when many civilian nuclear power

plants were planned and constructed. This period ended around the year 1990, when annual uranium requirements became larger than the annual extraction. During this period, uranium mining increased within a few years from 40 ktons to a production peak of almost 70 ktons/year around the years 1980/81. A production level of more than 60 ktons was maintained between 1978 and 1986 and a total of 1000 ktons were extracted between 1975 and 1990.

During the third period (1990-2005) the construction of new nuclear power plants essentially stopped at a capacity of about 374 GWe, far below the original ambitious plans in many countries from the 1970's. During this period and due to depletion and environmental reasons, uranium mining stopped in many productive regions and countries in Europe, Africa and North-America. Mining was reduced to an average of about 35 ktons/year, well below the uranium demand of 65 ktons/year, and a total of 500 ktons were mined.

During the past five years about 250 ktons of uranium were produced and the fast rising contribution from Kazakhstan from 4.4 ktons in 2005 to almost 18 ktons in 2010 might be used as an indication that a new production period has started.

2.1 Uranium depletion I: Europe and Africa

Uranium mining in Europe ended during the 1990's, and a total of about 460 ktons had been extracted when the last mines closed [6]. As can be seen from Figure 1 (left), production reached peak of more than 12 ktons/year in 1976 and maintained a production of about 10 ktons/year up to about 1990 from where it steeply declined to less than 1000 tons in the year 2000.

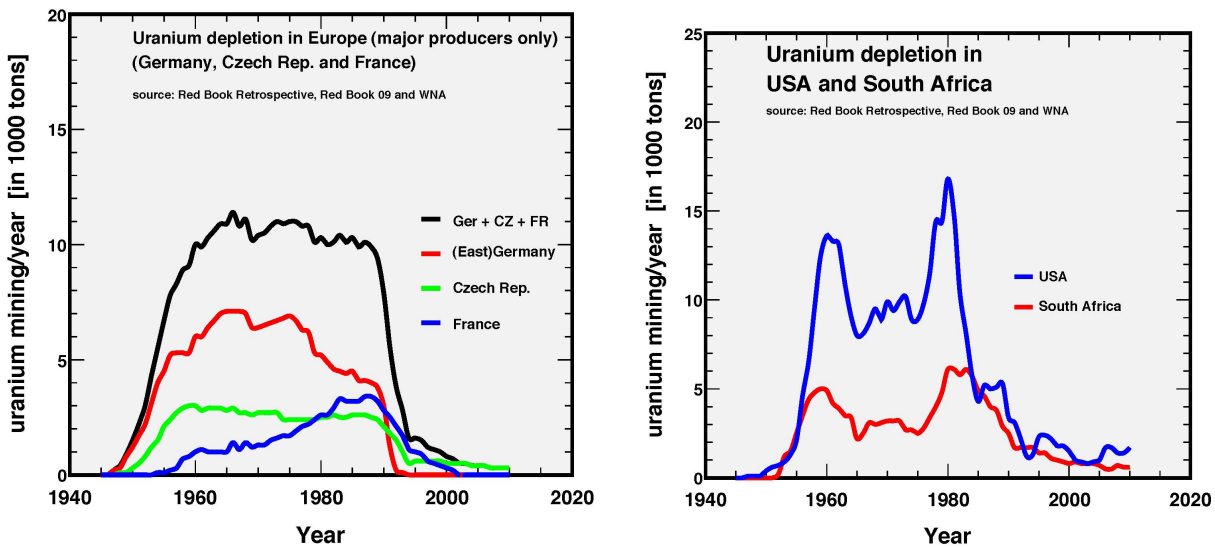

Figure 1: Historic uranium production data for Europe (left), the USA and South Africa (right).

The fact that essentially all of Europe's required 21 ktons/year uranium, [7], must now be imported is worth noting since it demonstrates that uranium, like the fossil fuels, is a finite resource that does not somehow magically appear in greater quantities just because demand pushes its price higher. As with the fossil fuels, the mining data from Europe show that deposit depletion and production declines are unavoidable consequences of finite resources.

The depletion of mineable uranium in Europe also makes is rather easy to compare original uranium resource estimates for all major uranium producing countries in Europe[8] with the achieved total amount of produced uranium. As can be seen from Table 1, mining stopped

when 50-70% of the initial deposit estimates had been mined. A similar conclusion can be drawn about the smaller but formerly important mines in the D.R. Congo and Gabon[8].

The pollution and radioactive remains from these past quick and dirty profitable mining activities leave at least a heavy moral responsibility for those who profited during the past decades from this cheap uranium.

country	demand 2010 [ktons]	peak production [ktons] (year)	initial resource estimate [ktons]	extracted total [ktons]	extracted fraction
Germany	3.45	7.1 (1967)	334.5	219.5	66%
Czech Rep.	0.68	3.0 (1960)	233.4	109.4	47%
France	9.22	3.4 (1988)	110.8	76.0	69%
Bulgaria	0.28	0.65 (1985-1988)	49.1	16.4	33%
Hungary	0.30	0.6 (1960-1983)	32.8	21.1	64%
Romania	0.18	2.0 (1956-1958)	37.1	18.4	49%
Spain	1.46	0.26(1994-2000)	26.4	5.0	19%
West. Europe	21	12.3 (1976)	≈ 810	≈ 460	58%
D.R. Congo	-	2.5 (1951)	33.5	26.5	79%
Gabon	-	1.1 (1979)	27.9	25.4	91%
USA	19.4	16.8 (1981)	1651.8	366.8+472.1*	51%
South-Africa	0.32	6.1 (1981)	444.2	157.4+195.2*	79%

Table 1: Uranium mining data[5, 6, 7, 8] from countries where mining came to an end many years ago. The extracted amount of uranium reaches between 50-70% of the amount originally estimated. The data for the USA and South Africa, where the annual mining results have been for many years at less than 10% of their previous peak production years, are also given. As mining has not yet stopped in both countries, the maximal extractable fraction with respect to the original amount estimated is obtained from the uranium extracted so far and adding their RAR* resources.

2.2 Uranium depletion II: USA and South Africa

Uranium mining in 2010 in the USA and in South Africa provided 1.7 ktons and 0.6 ktons respectively[5], namely about 10% compared to their peak production at the beginning of the 1980's when 16.8 ktons (USA) and more than 6 ktons/year (South Africa) were mined. Including 2010, mining operations in the USA have extracted a total of 366.8 ktons and the remaining reasonable assured resources, RAR, are given as 472.1 ktons[7]. Both numbers together are much smaller than the original in-place estimate for the known deposits in the USA which was 1651.8 ktons[8]. For South Africa the total extraction so far is given as 157.4 ktons and the remaining RAR resources are estimated to be 195.2 ktons. Again, the sum of both numbers is significantly smaller than the original deposit estimate of 444.2 ktons[8].

Moreover, in light of the fact that annual production has declined steeply to roughly 10% of the peak level that was achieved in the 1980s, the present RAR numbers do not appear to be realistic. Another indication that they are not realistic comes from the very large difference between the present production of the USA and South Africa and the claimed mining capacities in those two countries which are roughly 2.5 and 10 times larger respectively.

It is also important to note that, despite their roughly equal RAR numbers, uranium production in the USA reaches at most 20% of that from Canada. Similar conclusions about the RAR numbers are obtained when one compares uranium production in South Africa with the currently much larger production of Namibia and Niger.

3 A hypothesis about the mining of uranium deposits

With a few exceptions, annual mining results from individual mines are publicly available only for the past few years. The better documented data from uranium mining centers in Saskatchewan (Canada) and Australia are summarized in Table 2[9]. The data from the long established mining centers show that the mining was actually undertaken on several nearby deposits. These deposits were exploited successively and in such a way that a relatively stable level of production was sustained over decades.

Name (deposit)	initial estimate [ktons]	extracted total [ktons] (years)	plateau value [ktons]	estimated total [ktons]
Rabbit Lake (main)	10-25	15.8 (74-84)	1.4*	14 ± 3
Collins B	10-25	11.3 (85-91)	1.9*	19 ± 4
Collins A+D	7.5-15	8.6 (95-97)	2.0-3.2*	26 ± 6
Eagle Point	25-50	24.9 (92-98 +03-10)	2.5-3.0*	27.5 ± 6
Rabbit Lake (all)*	52.5-115	60.6 (74-10)	4.5*	86.5 ± 10
Cluff Lake (5)	14.5-30	10/14.4 (80-92/92-03)	1/1.4*	$(10 + 14) \pm 5$
Key Lake (1)	25-50	32 (83-87)	6.4*	64 ± 13
Key Lake (2)	25-50	42 (89-01)	5.4	54 ± 11
Mc Clean Lake (1)	10-25	19.2 (99-10)	2.35	23.5 ± 5
McArthur (Zone 2)	≈ 100	73.6 (99-10)	7.2	72 ± 14
Ranger (Number 1)	25-50	36.9 (80-95)	2.8	28 ± 6
Ranger (Number 3)	> 100	55 (97-2010)	3.8-4.8	48 ± 10
Olympic Dam	300**	50 (88-98/99-2010)	1/3	$(10 + 30) \pm 8$
Beverley	10-25	6.5 (01-10)	0.9***	9 ± 2

Table 2: Key data for the main deposits from several well documented recent uranium mines and deposits in Saskatchewan/Canada and Australia[9]. Not all details about the annual individual deposit mining are available, and the plateau value is approximated from the average* annual production. The amount of the initial estimate** for Olympic Dam takes the entire content down to a depth of about 1000 m. So far only the "surface" layer(s) have been touched. The value of 0.9 ktons/year for the plateau of the Beverley*** mine was obtained only for one year. The 2010 result of less 0.4 ktons indicates that the mine will not achieve anything close to the original plans. The last column gives the mining model (section 3.1) estimate for the total extraction, obtained from the plateau value multiplied 10.

Taking the essentially depleted Rabbit Lake (1975 - 2010) mining center as a typical example one finds that the uranium mined came from 5 medium to high grade deposits ($> 1\%$), discovered between 1968-1980. The larger deposits Rabbit Lake (1975-84) and Collins Bay B zone (1985-91) were totally exploited after 9 and 6 years and the smaller deposits Collins Bay A (1995-97) and D (1995-96) were depleted during 3 and 2 years respectively. Mining at Eagle Point started in 1994, was stopped between 1998-2002 and started again afterwards. The remaining uranium in place for closing mining activities up to 2015 has a much smaller ore grade (below 1%) and is estimated, with suspect precision, as 8.172 ktons.

The maximum production at the Rabbit Lake milling facility was about 4.5 ktons/year (1997/98), after which it decreased to less than 1.5 ktons/year during the years 2008-2010. The total production between 1975 and 2010 from the five deposits amounts to about 61 ktons. This is on the low side of the initial resource estimate, given as somewhere between 52.5 - 115 ktons.

The McArthur deposit, discovered in 1988, is currently the only remaining really productive uranium mining center in Canada. The deposits are located about 600 m underground and an estimated average ore grade,15.24%, is about 100 times larger than those of essentially all other deposits. The uranium is located in six close deposits, called Zone 1-4, Zone A and B. Mine construction started in 1997 and production from the largest deposit, Zone 2, began in 1999. The designed production plateau of 7.2 ktons/year was reached in November 2000 and a total of 73.6 ktons have been mined between 2000 and 2010. The estimates from the 2009 Cameco technical report[10] about Zone 2 indicate that the main body from Zone 2, Panel 1-3, will essentially cease production in the near future. Between 2011-2017, production will come from Zone 2, Panel 5, with a planned production plateau of about 4.5 ktons/year. The results from the first three months of 2011 show a production drop of about 35% when compared with the same period from 2010[11]. This decrease might be a natural consequence of the transition to a new Panel (deposit).

The corresponding data for the still active mines in Australia, Ranger, Olympic Dam and Beverley are also presented in Table 2. Perhaps with the exception of Olympic Dam, the conclusions about production profiles and mine depletion are similar to the one in Canada.

Uranium from Olympic Dam is defined as one huge very low grade deposit of 0.06%, lying deep underground. The uranium is distributed over a 3.5x5 km^2 area and lies between 260-1000 m below the surface. The huge volume is estimated to contain more than 2 million tons of uranium from which up to 300 ktons are counted as proved ore reserves. Uranium extraction is done in combination with copper and the low grade requires an open pit operation. Following the overall extraction profile, about 1 kton/year of uranium was extracted between 1988 and 1998 and more than 3 ktons/year after the year 2000. The actual mining could thus be considered as operating on deeper and deeper levels similar to the mining of several deposits.

3.1 The Hypothesis: Deposit exploitation and mining lifetimes

The exploration periods of different mines in Table 2 indicate that mining operations seem to be planned such that a relatively stable production plateau from a given deposit can be maintained for at least five years. Assuming that the mining companies use more accurate and partially secret geological information about the deposits and design the mining infrastructure in such a way that costs are minimized, we propose a working model for the mining of uranium deposits:

- The plateau production can be sustained for 10 ± 2 years. The assumed lifetime uncertainty is guessed from the few years of lower extraction during mine start-up and termination.
- The total amount of extractable uranium is approximately the achieved (or for future mines, the planned) annual plateau value multiplied by 10.

Applying this hypothesis and using the different plateau values, the total estimated amount of extractable uranium from the different deposits is given in the last column of Table 2. Leaving the three special cases, Collins A+D, Key Lake(1) and Olympic Dam aside, the total produced uranium from all mines is about 310 ktons. This is in amazing agreement with our hypothesis which predicts 319 ± 24 ktons of extractable uranium.

For the two exceptions, Collins A+D and Key Lake(1), our model predicts much larger amounts than achieved. These deposits were only minor when compared to the main deposits nearby and the short mining periods indicate that the mining of these deposits were probably planned such that a smooth transition between the larger deposits was possible. Even though our model is so far also in good agreement with the mining at the Olympic Dam deposit,

because of this somewhat special very low grade deposit, we prefer to exclude this mine until more details become public.

4 Extraction profiles, the future demand/supply situation

The above model (hypothesis) can now be applied to the larger currently operating uranium mines and the ones which are in a serious planning phase. Considering that the achieved plateau values from past operations were usually smaller than the ones planned, our model probably overestimates the future production. Furthermore, as in the past, the planned start-up dates for new mines are uncertain and delays of several years are common. It follows that the results from our model should be understood as a likely upper limit for the achievable uranium production during the next two decades. The predicted uranium production for different important mining countries for the next 20 years are shown in Figure 2 and are summarized in Table 3. A few interesting details are discussed below.

Starting with mining in Canada up to 2030, assured production will come essentially only from the McArthur deposit, as large uncertainties are associated with the mining of deposits at Cigar Lake and Midwest. The detailed plans for the different McArthur deposits (Zones), [10], indicate that the mining of 4.5 ktons/year from the largest Zone 2 can continue up to 2016. Extraction from Zone 4 (lower) should start in 2011 and about 2-2.5 ktons/year should be added such that the current plateau value of about 7 ktons/year can be maintained until 2016. The mining of Zone 4 (upper) part should start around 2016 and should reach a 10 year plateau value of more than 2.5 ktons/year after 2020. Some time after 2015 the extraction from the smaller deposits in Zone 1 and Zone 3 should also start, adding about 1.5 ktons/year for both of them combined during the years 2019 - 2029. Assuming that the mining from the different Zones take place as planned, a continuation of the current annual production of about 7.2 ktons/year can be sustained until 2017. Around 2017 the production is predicted to drop by 40% leading to a new production plateau of 4.5 ktons/year until 2030. Between 2030-2033, production will end with an annual decrease of roughly 1.5 ktons/year. The plans assume optimistically that about 90 ktons, or about 100% of the remaining proven and probable reserves, can be extracted during the next 20 years.

Perhaps the most unlikely detail about this two-decade plan, [10], is that the uranium grade required to achieve the goals has to increase from an average of 15% exploited during the last ten years to 23% from 2020-2023 and further to more than 29% for the remaining years. When one considers that after 2020 a large fraction of the uranium has to come from the less well understood deposits, the required transition to mining of much higher uranium grade looks extremely unlikely, and we predict that real production from the McArthur mine in the new Zones will be significantly lower than the 4.5 ktons/year expected after 2016.

The Cigar Lake deposit looks in many respects similar to the McArthur deposit. However, this deep deposit is located in very poor underground conditions and severe flooding incidents have delayed the original mining plans so far by almost ten years. The latest indications from Cameco assume that mining can start at the end of 2013 and reach full production of 7 ktons/year a few years later (2017?).

According to our model we find that the total extractable amount will be about 70 ± 14 ktons. This number matches well with the one given for the proven and probable reserves of about 80 ktons. It follows that the current mining plans do currently not consider the additional 52 ktons of inferred resources. We thus predict that this mine will stop production about ten years after the production plateau is reached.

A few other much smaller deposits in Canada are currently under study. But, even the

plans for the most advanced Midwest project, with measured and indicated resources of about 16 ktons, are now rather unclear.

Assuming that Cigar Lake and Midwest can start around 2017 and 2020 respectively, uranium mining in Canada will decline from last year's 9-10 ktons/year (2006-2011), [5], to about 7.5 ktons/year during the next six years (2012-2017). Once Cigar Lake and Midwest start, production can increase again to at most 11 ktons/year up to 2027, whereupon it will decline to 3 ktons/year or less by 2030.

For the mines in Australia[12] we expect that the decline observed at Ranger, Beverley and the "old" Olympic Dam mine will continue during the next few years and production will cease around 2015. Perhaps the most interesting project for uranium mining is the Jabolanka deposit in or near the world heritage Kakadu National Park. However, this project is currently on hold and strong opposition might not allow to open it during the next decades.

The largest future project in Australia (and on the planet) is the mega Olympic Dam project[13], a giant open-pit mine, up to 1000 m deep, which might eventually produce up to 16 ktons/year. The plans are currently rather badly defined, and we assume that an increase to more than 3 ktons/year can at best be imagined after 2020. Another eight smaller deposits, with a combined reserve estimate of about 80 ktons, appear to be in a more serious planning phase and some of them might start during the next few years. We assume that the mining of these deposits will be stretched over the next decades such that in combination with Olympic Dam a total production of about 6 ktons/year can be maintained beyond 2030.

Uranium production in Kazakhstan, [5], rose in a spectacular way from about 1 kton/year (1997) and 4.4 ktons (2005) to make the country the worlds largest uranium producer in 2009. The almost 18 ktons produced in 2010 came from the mining of more than 20 smaller deposits and exceeded the production from Canada and Australia combined.

According to the 2009 Red Book[7], the numbers submitted from this country, indicate that this spectacular rise can continue only for a few more years and will decline after a peak production of about 28 ktons in 2015 to 24 ktons (2020), 14 ktons (2025), 12 ktons (2030) and 5-6 ktons in 2035. The latest 2011 announcements from the State-owned mining company, Kazatomprom, are already significantly smaller than the ones from the Red Book and mining is now expected to yield 19.6 ktons in 2011 and 20 ktons in 2012. After 2012 mining will stay around the plateau value in the *neighborhood* of 20 ktons (reaching at most 25 ktons)[14].

In the absence of precise data from individual mines, we presume that a plateau value of 22 ± 2 ktons will be maintained until 2015. Using the start-up and plateau data summarized in reference [15] we find that a decline of roughly 1 kton/year for every year after 2015 will be unavoidable. Mining will decrease accordingly to 17 ± 2 ktons around 2020, 12 ± 2 ktons in 2025 and to 7 ktons or less in 2030. This predicted decline happens about five years earlier than the one predicted by the Red Book, but given the large uncertainties regarding past and current individual mines in Kazakhstan, the two predictions might be seen as in the same ballpark.

Besides the projects in Canada, Australia and Kazakhstan, five mines, [5], with more than 1 kton/year production are currently in operation: Rossing and Langer Heinrich in Namibia, Arlit and Akouta in Niger and Kraznokamensk in Russia.

The Rossing mine, which began production in 1976, is often presented as a proof that uranium can be mined efficiently down to grades of 0.03%. Mining operations cover two large (50-100 ktons and 25-50 ktons) and two smaller deposits (5-10 ktons). Current plans for this mine indicate that production can be maintained up to about 2016 and perhaps up to 2021. A more careful analysis of the data from this deposit reveal the special character of this mine. According to a 2009 report[16] the large very low grade deposit contains many small clusters of uranium with grades of about 1%. Thus it is most likely that it is mainly these higher-grade clusters that are mined while an overall average grade is reported. In the absence of better data we assume that the 2010 production value can at best be sustained until 2020.

The Langer Heinrich mine started production in 2007, and 1.4 ktons were produced in 2010. The plateau target is about 2 ktons/year. Following our model, this mine will cease production around 2020 with a plateau value of 1.7 ± 0.3 ktons/year.

Several large low-grade deposits are associated with the two older mining centers Arlit and Akouta in Niger. Production started around 1978 and was increased after 2003. Both centers together produced about 4.2 ktons in 2010. Taking a plateau value of about 4 ktons/year the currently estimated proven reserves allow that full production can be maintained until about 2016 and decrease afterwards. The current plateau production would thus roughly match the ten-year lifetime model for both mining centers.

The last operating uranium center in Russia is Kraznokamensk, Eastern Siberia, where several deposits have been exploited since decades and the legacy of the related environmental problems are detailed in an article by H. Högelsberger [17]. The remaining total reserve estimates are given as more than 100 ktons and according to a WNA document[18], the plateau production of around 3.5 ktons/year coming from several deposits in this area can be maintained or perhaps even slightly increased up to at least 2025.

Concerning other future mines around the planet one finds that seven larger mines, and up to 20 smaller facilities with capacities ranging from a few hundred tons to slightly more than 1 kton/year, are in the planning phase [19]. Of the seven larger mines, three, with capacities around 5 ktons/year, are planned for Niger (Imourain 2012), Namibia (Husab 2013) and Russia (Elkon 2015), and four, located in Namibia, Jordan, Russia and the Ukraine, will have a combined capacity of about 7-9 ktons/year. The original start-up plans for these mines have already been delayed by several years.

In absence of more detailed data we assume that production in Russia can be increased around the year 2015 when the production from the Elkon mine will begin[20].

For all other future facilities outside of Kazakhstan, Canada, Australia and Russia we assume that their future production will just allow them to compensate for the depletion of the smaller mines operating today and that the combined production in all other countries can be kept at today's level of about 17 ktons/year up to 2025-2030.

Following our model and combining all countries, we predict a peak uranium production of 58 ± 4 ktons/year (or with 95% probability less than 66 ktons/year) around the year 2015.

Country	production 2010 [ktons]	forecast 2015 [ktons]	forecast 2020 [ktons]	forecast 2025 [ktons]	capacity 2030 [ktons]
Kazakhstan	17.8	22 ± 2	17 ± 2	12 ± 2	7 ± 2
Canada	9.8	9 ± 1	10 ± 2	10 ± 2	3 ± 2
Australia	5.9	4 ± 1	6 ± 3	6 ± 3	6 ± 3
Russia	3.6	6 ± 2	6 ± 2	9 ± 3	9 ± 3
all others	16.6	17 ± 2	17 ± 2	17 ± 2	17 ± 2
World (max)	53.7	58 ± 4	56 ± 5	54 ± 5	41 ± 5

Table 3: Uranium production forecast following the Ten-year production model and some guesswork for the start-up and performance of announced future uranium mines. The highest prediction for the year 2015 and the decline should be understood as a maximum upper annual production limit during the next 20 years.

4.1 Uranium demand and other supply estimates

Table 4 shows the worldwide uranium demand up to 2030 under a slow nuclear growth (+1%/year) and under a nuclear phase-out scenario (-1%/year). The supply forecast from our ten-year pro-

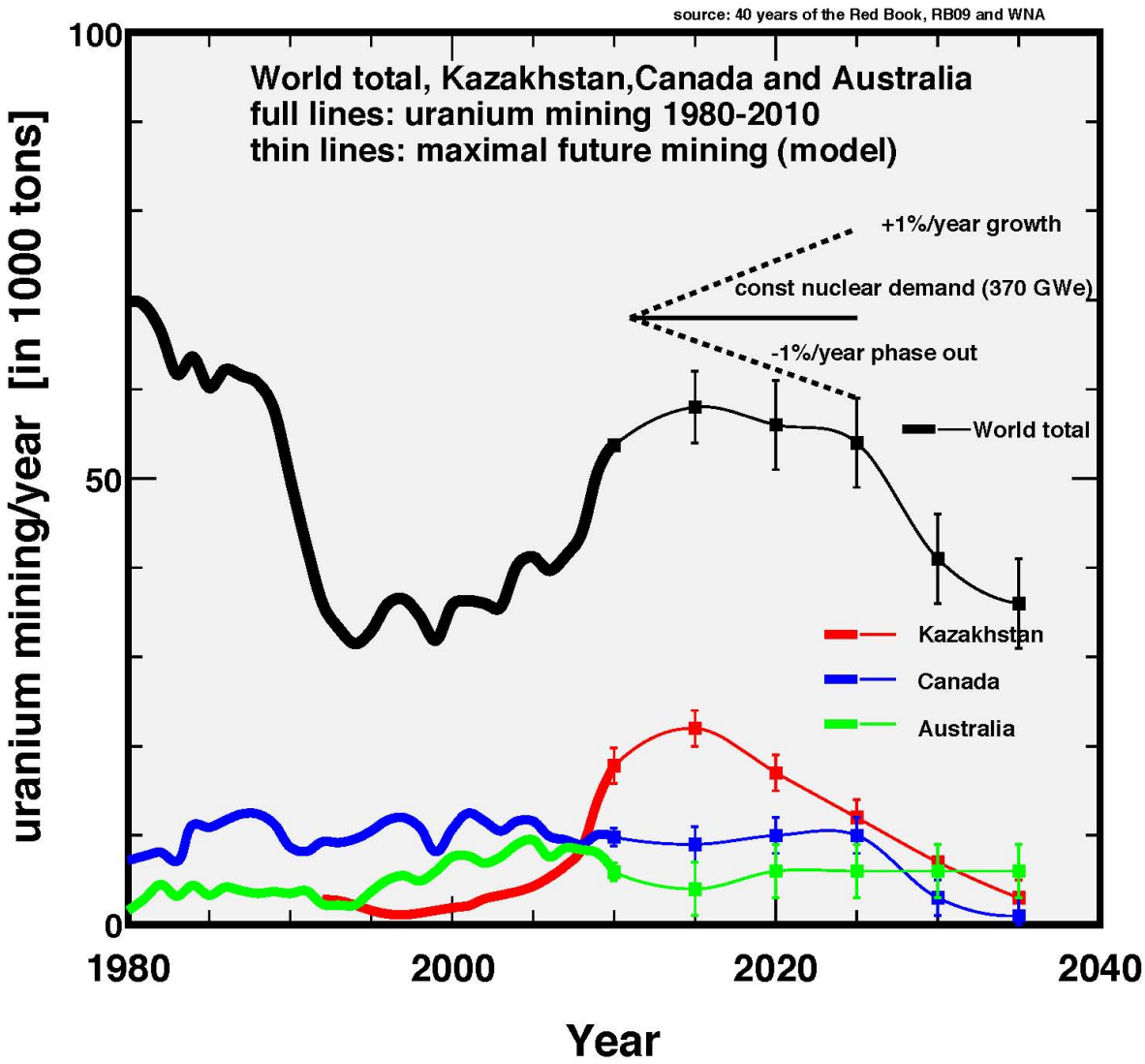

Figure 2: Past and predicted (this model) uranium production in different countries and for the planet combined. Details about future uranium demand scenarios are discussed in the text.

duction model and the ones from other forecasts are also listed.

The following considerations are important when one compares the different forecasts.

The WNA 09 forecast[21] differs from our model mainly in the assumption that existing and future mines are assumed to have a lifetime of at least twenty years. As a result a production peak of 85 ktons/year is envisaged about ten years later and around the year 2025, followed by a steep decline to about 70 ktons/year in 2030. This prediction could be understood as a warning about the limited uranium supply, which by 2030 can only fuel nuclear reactors with a capacity similar to the ones of today. In any case the long deposit lifetime in the WNA 09 model is inconsistent with the data presented in Section 3.

The 2006 estimate from the Energy Watch Group (EWG)[22] was based on the Red Book 2005 RAR and IR (inferred resources) numbers. An upper production limit was obtained from the assumption that mining can be increased according to the demand until half of the RAR or at most half of the sum of the RAR+IR resources are used. Accordingly, a production peak at latest around the year 2025 is predicted. As shown in Section 2, a production profile based

Scenario	production 2010 [ktons]	forecast 2015 [ktons]	forecast 2020 [ktons]	forecast 2025 [ktons]	capacity 2030 [ktons]
Demand +1%/year	68	71.5	75	79	83
Demand -1%/year	68	65	61	58	55
this model (max)	53.7	58 ± 4	56 ± 5	54 ± 5	41 ± 5
WNA 09	53.7	70	80	85	70
EWG 06 (RAR-IR)	53	63-65	68-72	70-88	65-84
RB 09 (capacity)	70-75	96-122	98-141	80 -129	75-119
RB 09/75	53-57	72-91	74-106	60-97	57- 89
RB 09/N50	52	63-76	64-85	55-77	53-72

Table 4: The uranium demand stands either for the demand or the production up to 2030 and for a slow ±1%/year nuclear growth/phase-out scenario. Our forecast model is the only one based on the data from past mining experience and indicates that even with an unchanged nuclear capacity a demand of 68 ktons/year uranium shortages can essentially only be avoided if the supply from Russian and USA military reserves will continue after 2013. The other supply scenarios are discussed in the text.

on claimed RAR numbers is inconsistent with the production in the USA and South Africa. We presume that the EWG study would be more consistent with our forecast if realistic RAR data were available.

The largest upper production limit with large uncertainties comes from the Red Book capacity scenario[7]. It is acknowledged by the authors of the Red Book that the capacity number given by the different countries is unreliable and much larger than real mining results. For example, the ratio between the 54 ktons mined in 2010 and the Red Book 09 capacity for 2010 varies between 0.71-0.77. In order to use these numbers nevertheless we presented two methods to use the mining capacity numbers for a forecasts[23]. The RB 09/75 scenario scales all future capacity estimates according to the 2010 ratio and with a factor of 0.75. Alternatively the RB 09/N50 scenario assumes that the 2009 mining result of 50 ktons can be sustained for many years and the new mining capacity will be realized with a factor of 0.5. Both, the RB 09/75 and the RB 09/N50 scenarios should only be considered as rough guesses on how the totally wrong capacity numbers might be used to obtain a approximate forecast for upper production limits.

When comparing the different forecast, we observe that only our simple ten-year lifetime model, by construction, fulfills the condition to be consistent with the historic uranium mining data. Consequently we conclude that our approach provides currently the most realistic upper uranium production limit.

5 Summary

The data about terminated uranium mining in different countries and regions demonstrate that on average only 50-70% of initial uranium resource estimates can be extracted.

Using the more precise data about the uranium extraction from recent individual mines and deposits in Canada and Australia a depletion model for modern uranium mines can be derived. This model states that modern mines minimize the extractions costs such that the mining of a given deposit result in (1) an effective lifetime of 10 ± 2 years and (2) the total amount of extractable uranium from a given deposit can be approximated by the achieved (or planned) annual plateau value multiplied by 10.

This model is applied to existing and planned uranium mines and an upper production limit for uranium extraction in different countries and for the entire planet is obtained up to 2030. In detail we find that:

- A production decline from essentially all mines operating on particular deposits is unavoidable during the present decade.
- This decline can only be partially compensated by the planned new mines.
- Assuming that all new uranium mines can be opened as planned, annual mining will be increased from the 2010 level of 54 ktons to about 58 ± 4 ktons in 2015.
- After 2015 uranium mining will decline by about 0.5 ktons/year up to 2025 and much faster thereafter. The resulting maximal annual production is predicted as 56 ± 5 ktons (2020), 54 ± 5 ktons (2025) and 41 ± 5 ktons (2030).

Assuming that the demand side will be increased by 1% annually, we predict both shortages of uranium and (inflation-adjusted) price hikes within the next five years.

A way to delay a supply crunch until 2025 could be a voluntary nuclear energy phase-out in many countries. Such a phase-out of conventional U235 based nuclear power plants appeared to be very unlikely at the beginning of 2011, but the recent accident in the Japanese Fukushima nuclear power complex could lead to totally different prospects.

Another alternative to avoid shortfalls during this decade would be a "wider" opening of the still sizable quantities of the military uranium reserves from the USA and Russia especially after 2013. The military uranium reserves have been estimated in a 2009 paper, [24], to be roughly 200 ktons for the USA and 300 ktons for Russia. Although any such increases involve political issues that clearly go beyond the scope of our analysis, this source, depending on the demand growth, could in principle delay uranium shortages for several years. However, it is obvious that these strategic military reserves are very finite and it seems unlikely that they will be opened easily for the demand in China and Europe.

Therefore, assuming that a global nuclear slow phase-out scenario will not be chosen on a voluntary basis, we predict that the end of the cheap uranium supply will result in a chaotic phase-out scenario with price explosions, supply shortages and possible electricity shortages in many countries.

Acknowledgments

This analysis is a result of many, mostly unfruitful, discussions with pro nuclear enthusiasts about uranium being a finite resource like fossil fuels and about the difference between actual and future uranium mining and the exploitable amounts of uranium in the earth crust.

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