The Future of Nuclear Energy: Facts and Fiction - Part II: What is known about Secondary Uranium Resources?

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During 2009, nuclear power plants, with a capacity of 370 GWe, will produce roughly 14% of the world-wide electric energy. About 65,000 tons of natural uranium equivalent are required to operate these reactors. For the last 15 years, only 2/3 of this fuel has on average been provided by uranium mines, whereas 1/3 has come from secondary resources. According to the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD), the secondary uranium resources will be essentially exhausted during the next 5-10 years. In this paper, the situation concerning the secondary resources at the beginning of the year 2009 is presented. The data used are from the IAEA/NEA 2007 Red Book, "Uranium Resources, Production and Demand," and from the World Nuclear Association (WNA).

Our analysis shows that, at the beginning of 2009, the remaining world-wide civilian uranium stocks amount to roughly 50,000 tons. With the almost inevitable yearly draw-down of 10,000 tons, these civilian stocks will be essentially exhausted within the next 5 years. This coincides roughly with the year 2013, when the annual delivery of 10,000 tons of natural uranium equivalent from Russian military stocks to the USA will end. As the majority of the remaining civilian stocks, about 30,000 tons, are believed to be under the control of the US government and American companies, it seems rather unlikely that the USA will share their own strategic uranium reserves with other large nuclear energy users. In summary, all data indicate that a uranium supply shortage in many OECD countries can only be avoided, if the remaining military uranium stocks from Russia and the USA, estimated to be roughly 500,000 tons, are made available to the other countries.

(Link to 1st part)

Introduction

In part I of this analysis, we have described the world-wide situation of nuclear energy production, the status of uranium mining, and the near future perspectives and limits. In this part, we quantify the situation concerning secondary uranium resources, which have provided for the past 10-15 years the fuel for about 1/3 of the world's nuclear reactors. The current nuclear fuel situation is, according to official documents from the IAEA and the NEA, totally unsustainable, and the existing secondary resources are expected to be exhausted within the next few years. The seriousness of this situation, largely ignored by the media, has been expressed in the IAEA and NEA press declaration of June 3, 2008, launching the 2007 edition of the Red Book [1], [2]:

> "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."

In order to clarify the importance of the secondary uranium resources, some facts about nuclear fission energy are summarized below [3]:

- Commercial nuclear reactors are operated in 31 out of the 200 countries on our planet. In 2009, 436 nuclear power plants, with a net installed capacity of 370.2 GW electric power, are in operation. These reactors provide about 14% of the electric energy produced world-wide.
- During the past 5-10 years, nuclear power capacity remained essentially unchanged, as the capacity increase from new reactors was compensated for by the shut-down of many old reactors. In contrast to a claimed "nuclear renaissance," 2008 was the first year since at least 40 years, when not even one new reactor was connected to the electric grid.
- The absolute world-wide production of electric energy from nuclear fission has, according to the WNA data base, reached a "peak" in 2006, when 2658 TWhe were produced. This amount can be compared with the years 2005, 2007, and 2008 when, 2626 TWhe, 2608 TWhe, and 2601 TWhe were generated, respectively [3].
- The world-wide reactor requirements for the two fissionable isotopes U235 and Pu239, expressed in terms of natural uranium equivalent, are currently 65,000 tons, or about 170 tons/GWe, per year. For more than 10 years now, the primary uranium supply from world-wide mining has provided only about 2/3 of the requirements, whereas 1/3 stems from the draw-down of secondary sources, a huge amount corresponding to almost the total uranium extracted by the three largest uranium producing countries, Canada, Australia, and Kazakhstan, together.
- Out of the 31 countries operating nuclear power plants in 2006, only Canada, South-Africa, and Russia were uranium self-sufficient. The other countries use a mixture of uranium imports and previously accumulated uranium stocks.
- Nuclear power plants in Japan, South-Korea, and the Western European countries, which have little or no uranium mining and have little or no civilian and military uranium stocks, are particularly vulnerable to uranium supply shortages.
- About 48 reactors are under construction today, and up to 60 reactors are in a discussion and planning state. If one assumes that all of the 48 reactors under construction can be completed in time, between 5-10 GWe/year should become operational during the next 5-10 years. These reactors would require roughly 500 tons of natural uranium per GWe for the first load and 170 tons/year during the following years. About 5000 tons/year of uranium will thus be required on average for their startup and operation. If one assumes that the 100 oldest nuclear reactors are not shut down, the yearly uranium demand will increase from 65,000 tons in 2008 to about 90,000 tons by 2015.

In the following, we shall analyze the status and prospects for the possible contribution from secondary uranium resources using the data from the IAEA/NEA Red Book 2007 edition and from WNA information papers. First, we present the current composition of the secondary resources by using publicly available information about past uranium extraction, and we determine the 2009 status of uranium stocks. Then, we combine the information from the secondary supplies with the mining expectations and make a quantitative prediction for the uranium supply situation and its consequences for nuclear power plants during the next 5 years.

The composition of secondary uranium resources

As explained above, secondary uranium resources provide the fuel for about 1/3 of the world's nuclear fission power plants. These secondary uranium resources are classified as follows:

- nuclear fuel produced from reprocessing of reactor fuels and from surplus military plutonium;
- U235 produced by re-enrichment of previously depleted U235 uranium tails; and
- civilian and military stocks of natural uranium, weapon-grade enriched uranium, and Pu239, accumulated during excess mining operations in the past 50 years.

According to the Red Book, about 3500 tons (5% of world-wide demand) stem from reprocessing and from depleted uranium tails. An expansion of such production facilities would, like other big nuclear power projects, require at least 5-10 years. Such an expansion is currently not planned.

Pu239/U235 from the reprocessing of used fuel rods

In order to operate a standard nuclear reactor, the nuclear fuel U235 (or Pu239) has to be enriched to a concentration well above the concentration of 0.71% found in natural uranium. New U235 enriched nuclear fuel rods contain a fraction of about 4% of the fissionable U235 isotope and 96% of U238. During the reactor operation, the U235 concentration will be reduced down to roughly 1%. At the same time, Pu239 builds up to an equilibrium concentration of about 1%. The Pu239 is formed by neutron capture of U238 isotopes and subsequent nuclear β decays. During the normal reactor cycle, the Pu239 component contributes up to 30% of the produced fission energy. After a few years of operation, the fissionable material has been reduced to about 2%, and some new fuel is usually introduced. Consequently, the used fuel rods still contain an interesting amount of fissionable material of U235 and Pu239. However, nuclear fuel recycling is a rather delicate and costly operation, as the fuel rods contain a large number of different radioactive elements. Another problem with this recycling is related to the military use of the Pu239 component. In the past, up to 95% of the extracted Pu239 was used for military purposes, where extraction costs and associated risks were considered less of an obstacle. Besides the huge cost, the potential military use of Pu239 limits the world-wide enthusiasm for nuclear fuel recycling.

However, at least some of the extracted Pu239 is used to produce the so-called "MOX" reactor fuel, a mixture of plutonium and uranium oxides [4]. Even though most current reactors could in principle be operated with MOX fuel, only 8% of the world-wide reactors are currently licensed to use this fuel. For example, the Euratom Supply Agency (ESA) reported that, within the EU-15 countries, reprocessing has produced a total of 95.8 tons of Pu239 since 1996. This amount corresponds to an equivalent of 11,515 tons of natural uranium. The ESA reports that the natural uranium requirements of the EU-15 reactors have been reduced in 2006 by 1225 tons, corresponding to about 5% of total fuel use, with this MOX fuel [5].

According to the Red Book, acknowledging that not all countries have reported their data, the world-wide capacity of Pu239 recycling is about 2500 tons/year of natural uranium equivalent.

Another source of "MOX" fuel, following an agreement in September 2000 between the USA and Russia, comes from military Pu239 stocks. Both countries agreed to convert 34 tons each at a rate of at least 2 tons per year. During the lifetime of this agreement, this contribution adds a natural uranium equivalent of roughly 600 tons to the secondary resources.

The used fuel rods also contain about 1% of U235. This uranium can be partly recovered as reprocessed uranium (or RepU). According to the 2007 Red Book, RepU processing is very costly and is currently done by France and Russia only. The yearly production capacity is estimated to be up to 2500 tons, but only 600 tons/year are currently being produced [6].

U235 from depleted tails

Depleted uranium tails are a by-product of the U235 enrichment process. The tails contain normally between 0.25-0.35% of U235, or about one third of the 0.71% contained in natural uranium. The inventory of depleted uranium is increasing every year by roughly 60,000 tons. It is estimated that roughly 1,800,000 tons have been accumulated in different countries by the end of 2008. In theory, a large amount of U235 is still contained in these tails, but the existing enrichment capacity is already rather limited. Nevertheless during the years 2001 to 2006, Russia delivered yearly up to about 1000 tons of re-enriched uranium to the European Union. According to the Red Book, the Russian Federation indicated that this delivery will be stopped once the existing contracts end. For the USA, a pilot project is anticipated to produce a maximum of 1900 tons of natural uranium equivalent during a period of two years. No additional information about the status of this or other world-wide projects is given in the Red Book.

Past uranium extraction and how it was used

In order to understand the uranium supply situation during the coming years, we need to know:

- how much uranium has been extracted in the past;
- how much of it has already been used up in reactors;
- the geographical distribution of these stocks; and
- how much of this excess capacity exists in civilian and in military stockpiles.

Partial answers to these questions can be obtained from different editions of the Red Book and from the WNA. Unfortunately, these presumably very precise numbers often do not agree with each other. For example in the Red Book 2007 edition, one finds two precise, but inconsistent, numbers for the amount of extracted uranium. The uranium mined up to the end of 2006 is given as 2,234,083 tons in chapter 1c (Table 19, page 39) and as 2,325,000 tons in chapter 2c (page 74), about 90,000 tons higher. A comparison with previous Red Book editions and the uranium mining results from 2005 and 2006 resolves the discrepancy in favor of the higher number. Unfortunately, such inconsistencies in the Red Book do not strengthen the confidence in the claimed accuracy for many other uranium numbers.

Next, we need to know how much of this uranium has been used up (fissioned) so far. According to the 2007 Red Book (chapter 2c), a total of 1,700,000 tons of uranium have been used up in reactors until the end of 2006. Thus, the total remaining stocks at the end of the year 2006 were 625,000 tons. During 2007 and 2008, the world's uranium mines produced 41,264 tons and 43,853 tons, respectively. Another roughly 7000 tons (3500 tons/year) came from recycling and reprocessing of depleted uranium tails. With reactor requirements of 65,000 tons/year, we find that the stocks have been reduced by roughly 40,000 tons. Out of this, roughly 20,000 tons came from the draw-down of Russian military stocks and another 20,000 tons from the draw-down of the remaining civilian stocks. Following this estimate, we find that, at the end of the year 2008, about 587,000 tons of natural uranium equivalent remain in the combined military and civilian stocks.

In order to understand the supply situation from these secondary resources during the next few years, it is important to know that the yearly delivery of 10,000 tons of uranium from the Russian military stocks will end in 2013. The future of the secondary uranium supply depends thus mainly on the size of the remaining civilian uranium reserves. Unfortunately, only a few countries have provided this information for the Red Book 2007 edition, but at least 43,844 tons (end of 2006) were attributed to civilian stocks. The majority of this amount, 41,279 tons, is assigned to the civilian stocks of the USA [7]. It is further specified that roughly one half of these stocks, or 17,796 tons, are owned by the US government, and that this amount is reserved to guarantee uranium supplies for their own reactors for two years. Assuming that the yearly draw-down of civilian stocks has continued during the past two years, we can expect that the stocks in the USA have been reduced to an amount of 25,000-30,000 tons. However, it is possible that this reduction was somewhat smaller as, unknown to the author, some contribution might have come from a conversion of military stocks of the USA.

Slightly more accurate numbers can be obtained, if we combine the well documented uranium data of the past eight years with those presented at the 2001 annual symposium of the World Nuclear Association [8]. In this document, the uranium associated to the civilian and military stocks of the Western and Eastern blocks has been estimated. The WNA analysis indicated that the civilian stocks at end of the year 2000 consisted of about 140,000 tons, out of which 117,000 tons should be associated with the Western block.

The WNA analysis started from a total of 1,999,000 tons of extracted uranium up to the end of the year 2000. This number is about 3% larger than the corresponding number of 1,938,000 tons given in the 2003 Red Book. The total reactor requirements up to the year 2000 were given as 1,138,000 tons, which is about 170,000 tons smaller than the amount that can be calculated from the 2007 Red Book estimate. The discrepancy between these two numbers might be understood from a different accounting of the remaining, not yet used, fissionable material in the reactors. The first uranium load requirement for a 1 GWe reactor is about 500 tons, but only about 170 tons are used and exchanged every year. Accordingly, one finds that the not yet used fuel within all existing 370 GWe reactor cores corresponds to an equivalent of up to 185,000 tons, in good agreement with the above discrepancy of 170,000 tons. In absence of a better number, we will thus use the 2007 Red Book number for the reactor used uranium and assume that the civilian uranium stocks at the end of the year 2000 were 140,000 tons.

During the past eight years, world uranium stocks have been reduced by about 170,000 tons, or about 21,000 tons annually. While about 80,000 tons came from a reduction of Russian military stocks, it can be assumed that the other 90,000 tons came mostly from Western civilian stocks.

It thus seems reasonable to estimate that, at the end of 2008, only 50,000 tons of civilian uranium stocks remain; out of these, about 27,000 tons are being controlled by the USA, whereas the remaining 23,000 tons are being controlled by Russia. If one subtracts this number from the total remaining stocks, the military stockpiles, shared somehow between the USA and Russia, can be estimated to be roughly 540,000 tons. Our estimate for the military stocks is at least 10% smaller than the amount that we would calculate from an update of the 2000 WNA estimates alone. If we assume that the percentage-wise distribution between the Eastern and Western military stockpiles from the year 2001 WNA analysis were roughly correct, the military stocks at the end of 2008 can be estimated. Taking into account that the Russian reserves have been reduced by about 80,000 tons and assuming that the military reserves are shared mainly between the USA and Russia, we can estimate their stocks at the beginning of 2009 to be 230,000 tons and 310,000 tons, respectively.

The above approximate numbers, as summarized in Table 1, indicate that the civilian uranium reserves, at the end of 2008, consist of roughly 50,000 tons. Furthermore, one finds that about 27,000 tons and 23,000 tons remain in the Western and Eastern civilian stockpiles, respectively. The military stocks can be estimated to be about 10 times larger and consist of roughly 540,000 tons of natural uranium equivalent.

	prod. uranium total [tons]	consumed uranium incl. [tons]	civilian stocks [tons]	military stocks [tons]
end of 2006	2325 000	1700000	$\geq$ 65000	560 000
2007/2008	85 200	123000	$\approx$ -18000	-20000
end of 2008	2410 200	1823000	$\approx$ 50000	540 000
western stocks			27000	230000
eastern stocks			23000	310000

Table 1: State of the uranium extraction and use up to the end of 2008, as estimated from the 2007 Red Book and WNA numbers for the years 2007 and 2008. Roughly 3500 tons/year of natural uranium equivalent is estimated to come from world-wide reprocessing, and this

amount is subtracted from the yearly requirements of 2007 and 2008. Taking into account that not all countries have reported accurate data to the Red Book and that some inconsistencies in the accounting exists, the civilian and military reserves contain perhaps an uncertainty of up to ±10%. The Eastern and Western stocks are believed to be controlled almost entirely by Russia and the USA.

The military uranium stockpiles

As described in the previous section, roughly 540,000 tons of natural uranium equivalent can be associated with the military reserves of the USA and Russia. Not all details about these military stockpiles are public, but some numbers relevant for the possible conversion of these stocks into reactor fuel can nevertheless be estimated.

Data from nuclear arms negotiations between the USA and Russia and other countries indicate that these two countries control currently roughly equal shares and a total of about 95% of all existing nuclear weapons [9]. For the following, it seems to be sufficient to only consider the military stocks of these two countries.

First, we estimate how much of these 540,000 tons of uranium is blocked in the remaining 20,000 nuclear warheads. It is known that the Hiroshima bomb was made of about 64 kg of uranium, with a U235 content of 51 kg (enrichment of 80%). This corresponds roughly to the critical mass, the amount required to start the uncontrolled chain reaction in a sphere of uncompressed bare metal of U235. Sophisticated methods for the uranium storage and controlled compression have reduced the critical mass by a factor of 2-3. In any case, the danger of uncontrolled explosions limits the amount of the U235 content in the warheads. It is also known that the nuclear fission bombs of today are based on U235 or Pu239, and that fusion bombs are started with an explosion of U235 or Pu239. On average, the nuclear weapons of today are estimated to have an explosive power at least 10 times stronger than the bomb that destroyed Hiroshima on August 6, 1945.

In absence of more precise data, we may assume that each nuclear weapon contains on average just the critical mass or at least 50 kg of U235. Using this assumption, we find that the U235 of one nuclear bomb corresponds to 7 tons of natural uranium equivalent on average, and that the uranium from about 25 such bombs is sufficient to operate a 1 GWe reactor for one year. Consequently, about 140,000 tons of uranium, about 1/3 of the military stockpiles, are currently blocked directly in nuclear weapons. Another large fraction of the military stocks can be assumed to exist as highly enriched weapon-grade uranium, HEU. In order to be used as normal nuclear fuel, these stocks would have to be downgraded to reactor-ready low-enrichment uranium, LEU, with a U235 fraction of 3-4%. During the past years, a natural uranium equivalent of 10,000 tons/year has been downgraded to reactor fuel, and this number may be considered roughly equal to the currently existing downgrading capacity. On a time scale of 5-10 years, it should be possible to increase this capacity.

Theoretically and assuming a total nuclear disarmament, the military uranium stockpiles would thus be sufficient to operate the current world nuclear reactors for about 8 years or for about 25 years assuming the current draw-down of secondary resources. Taking the current world real politics into account, such a total nuclear disarmament is unfortunately not very likely.

Nevertheless, the military stockpiles are certainly large enough, even without touching the remaining 20,000 warheads, that an extension of the current policy to convert about 10,000 tons/year can be imagined. It is however not obvious that either the USA or Russia will share their strategic uranium reserves with other users of nuclear fission energy. In addition, and with a longer term perspective, the downgrading of large amounts of previously highly enriched uranium seems to be pointless, as the original enrichment process was very expensive and as the highly enriched uranium might eventually be needed directly to fuel future Generation IV fast breeder reactors.

Secondary uranium supply, the near future

All existing data indicate that draw-down of the civilian inventories, practiced during the past 10 years, has reduced the civilian uranium stocks to roughly 50,000 tons. With an expected further yearly draw-down of up to 10,000 tons and without access to the military stocks, the civilian Western uranium stocks will be exhausted by 2013. Furthermore, the supply situation will become even more critical as the delivery of the 10,000 tons of military uranium stocks from Russia to the USA will also end during 2013. Thus we find, in agreement with the dramatic warning from the IAEA/NEA authorities, that secondary uranium supplies will essentially come to an end within a few years.

The severity of the supply situation seems to be known and acknowledged by the Uranium (Ux) Consulting Company (UxC) and by uranium mining co-operations. For example some interesting numbers about the evolution of demand and secondary supplies and the required primary uranium mining were presented in September 2008 at the annual WNA symposium [10]. The evolution of the secondary supply side was estimated to decrease by roughly 1000 tons per year starting from 20,029 tons in 2009 and ending with 15,008 tons by 2013. For the following three years up to 2016, a further reduction of about 2000 tons per year is assumed (the numbers for the years 2014-2016 are in disagreement with the 2013 termination of the yearly delivery of 10,000 tons from Russia). The authors of this WNA study assumed that many new reactors will start up during the coming eight years, and they estimate that the uranium demand will increase from 65,000 tons in 2008 to about 85,000 tons by 2013. Some of their uranium supply and demand estimations for the coming years are summarized in Table 2.

year	2008	2009	2010	2013	2014	2016
Macquarie guess	[tons]	[tons]	[tons]	[tons]	[tons]	[tons]
total primary	45145*	50216	54879	70004	76775	84632
total secondary	20015	20029	18315	15008	13000	9433
total demand	65159	70245	73194	88022	89775	94065
total capacity	365	379	382	409	427	477

Table 2: Forecast for the world uranium balance prediction for the years 2008-2016 according to the Macquarie Research Commodities predictions presented at the 2008 WNA annual sym posium [10]. The forecast for the 2008 primary uranium number(*) was about 1200 tons larger than the now known number of 43,853 tons. The latest WNA forecast for 2009 is 49,375 tons and thus also about 1000 tons smaller [11]. The claimed accuracy for the forecast should raise some doubts about the underlying methodology to guess these numbers.

As discussed above, the uranium supply might become the limiting factor for the near future of nuclear power production. This demand depends, among other things, on the future of the aging nuclear power plants and on how rapidly the reactors that are currently under construction can be completed. If the primary fuel supply cannot be increased as quickly as required, some interesting world-wide decisions about the future of nuclear power can be expected. For example, one needs to weigh the stable operation of older nuclear power plants, which require 170 tons/GWe/year, against the stability of early operations for new reactors that have a first load requirement of 500 tons/GWe. Of course, the situation will be further complicated by national and regional interests. It is difficult to imagine that the US government will sell their strategic uranium reserves to their economic competitors in Japan, China or Western Europe.

In absence of such political insights, one can nevertheless try to guess how much uranium fuel will come from different sources, and how many existing and new nuclear power plants can be operated with this fuel during the coming years. For this forecast, we make use of the uranium supply information presented in parts I and II of this document and assume that the demand will be limited by the possible supply. This "upper" limit guess is calculated on the basis that 170 tons/GWe/year are required to fuel an already operational reactor, and that 500 tons/GWe are needed for the first reactor load. This forecast is presented in Table 3 and can be compared with the one from Table 2. The main difference comes from the mining forecast and the assumption that the military component of the secondary supply from Russia will terminate by the end of 2013. Obviously the two scenarios should be checked and corrected for the real mining results during the coming years. Interested readers should fill Table 3 with their own favorite nuclear energy scenario under the constraint that it be consistent with their future secondary and primary uranium supply estimates.

year	secondary civilian [tons]	secondary military [tons]	primary (from year-1) [tons]	fuel for plants [GWe]	fuel for new "operating" plants [GWe]	expected production [TWhe]
2009	10000	10000	44000	370	2	2575
2010	8000	10000	≤45000	365	2	2550
2011	7000	10000	≤46000	365	2	2550
2012	7000	10000	≤47000	365	4	2550
2013	5000	10000	≤48000	360	4	2525
2014	5000	0(?)	≤49000	320	0	2250
2015	5000	0(?)	≤50000	320	0	2250
2016	5000	0(?)	≤50000	320	0	2250
2017	5000	0(?)	≤50000	320	0	2250
2018	5000	0(?)	≤50000	320	0	2250

Table 3: The author's upper limit forecast covering the years 2009-2018 for the world-wide natural uranium equivalent primary and secondary fuel supply and its consequences for nuclear fission produced electric energy in TWhe. This fuel-based scenario assumes that world-wide uranium mining cannot be increased as estimated by the IAEA/NEA and WNA. The result of this scenario will be a slow, about 1% annual, reduction of nuclear produced electric energy up to 2013. The decline will become much stronger after 2013, if military stocks will not add at least 10,000 tons annually to the fuel market.

Both scenarios obviously contain some guesswork, and many political and economic decisions during a world-wide economic crisis can change the near future of uranium mining and the evolution of the nuclear disarmament. Especially critical for uranium mining will be the situation in Kazakhstan, where the current optimistic forecast expects that by 2013 the existing and new mines will increase the uranium output from 8500 tons (2008) to about 18,000 tons annually. An increase of similar size is also hoped to come from the mines in Niger, Namibia, and South Africa [10].

In conclusion, uranium shortages and thus reactor shutdowns can be avoided only if world-wide uranium mining can be increased by roughly 10% or about 5000 tons each year. While such an increase looks rather unlikely for the next few years, the presented numbers for the required primary uranium in 2008 and the obtained results show a shortage of about 1200 tons indicating that up to 1400 tons will be missing already in 2009. This amount corresponds roughly to the reduction of the uranium requirements that followed the 2007 earthquake in Japan with an 8 GWe nuclear capacity outage.

We expect that the uranium supply situation will become especially critical for those countries where a large fraction of the electric energy comes from nuclear power and that important essentially 100% of their uranium needs. This supply problem will especially affect OECD countries in Western Europe and Japan. One might hope that discussions about new nuclear power plants will consider the warning from the NEA/IAEA press declaration about the Red Book 2007 edition expressed in the following paragraph:

> "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 drawn 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."

References

[1] 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 bookshop 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.

[2] Nuclear Energy Agency press declaration from 3 June 2008 about the new edition of the Red Book 2007 "Uranium 2007 Resources, Production and Demand" at http://www.nea.fr/html/general/press/2008/2008-02.html.

[3] For the year 2008 status and production of nuclear electric energy, cf. for example the WNA papers at http://www.world-nuclear.org/info/reactors.html, http://www.world-nuclear.org/info/inf01.html, and http://www.world-nuclear.org/info/nshare.html.

[4] For some details about MOX reactor fuel and further references, cf. http://en.wikipedia.org/wiki/MOX fuel.

[5] Cf. the EURATOM supply agency report 2006, page 24 at http://ec.europa.eu/euratom/ar/ar2006.pdf.

[6] Cf. reference [1], page 80.

[7] Cf. reference [1], page 367.

[8] Cf. the presentation of Bernard Del Frari The Global Nuclear Fuel Market Supply and Demand 2001-2020 at the 2001 WNA symposium http://www.world-nuclear.org/sym/01idx.htm.

[9] For an overview of the nuclear weapons and nuclear weapon states, cf. http://en.wikipedia.org/wiki/List_of_states_with_nuclear_weapons.

[10] Cf. the presentation of Maximilian Layton, Macquarie Capital Securities "The global uranium outlook: is 2008/09 a buying opportunity?" at the 2008 WNA symposium http://www.world-nuclear.org/sym/2008/presentations/laytonpresentation.pdf.

[11] Cf. the July 2009 version of http://www.world-nuclear.org/info/inf23.html.