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# The Future of Nuclear Energy: Facts and Fiction - Part I: Nuclear Fission Energy Today

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Nuclear fission energy is considered anywhere between the holy grail, that can solve all energy worries of the human industrialized civilization, and a fast path directly to hell. Discussions about future energy sources and the possible contribution from nuclear energy are often tainted and dominated by irrational expectations and fears. As a consequence, very little actual knowledge is available to the general public and even to decision makers about the contribution of nuclear energy today, about uranium supplies, uranium resources, and current and future technological challenges and limitations.

This analysis about nuclear energy and its future contribution attempts to shed some light on the nuclear reality and its limitations. The report, presented in four parts, is based on data provided in documents made available by the IAEA (International Atomic Energy Agency), the NEA (Nuclear Energy Agency of OECD countries), the WNA (World Nuclear Association), and the IEA (International Energy Agency).

Part I summarizes the state of the world wide nuclear fission energy today and its perspectives for the next 10 years; Part II presents the situation concerning secondary uranium and plutonium resources; Part III analyses the "known" uranium resource data as presented within the past editions of the IAEA/NEA Red Book; Part IV finally outlines the plans and prospects for the long term future of nuclear fission and fusion.

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## Introduction

Most people today agree that a comfortable way of life depends on the availability of cheap energy with its almost limitless applications. The average per capita energy consumption in the developed world increased by a factor of three or more during the past 50 years. However at most one billion people, or 1/7 of the human population of today, enjoy this increase. They live mainly in the richer countries and use on average approximately 50,000 kWh of thermal energy from various sources per year. This is three times higher than the world average consumption, roughly five times higher than the average per person energy use in China, and about 10 times larger than in India [1].

Depending slightly on the counting procedure, roughly 85% of this energy comes from fossil energy sources: about 40% from oil, 20% from natural gas and 25% from coal. Our mobility depends to almost 100% on oil. Electric energy, made from various "fuels," has the highest value for stationary applications and forms a basis for essentially all hi-tech and luxury energy applications. On a world-wide scale, electric energy accounts for 16% of the end energy use and between 20-25% in most of the rich countries. About 70% of the electric energy is again made from fossil fuels, about 16% from hydropower, and only 14% from nuclear fission energy. The renewable wind, solar, and geothermal energy sources, with some minor local exceptions, contribute no more than 1-2% to the energy mix [2].

These numbers demonstrate that electric energy, especially the part of it that is made from nuclear energy and renewable energy sources, contributes only little to the total world energy mix. In contrast, one obtains a totally distorted picture of their importance when one follows the media coverage and the political discussions at all levels about the pros and cons of nuclear fission power, hydropower, wind power, geothermal, and direct and indirect solar energy sources. For Switzerland, an interesting example of a small, densely populated and rich industrialized country, one finds that electric energy contributes to roughly 24% of the final energy mix. Electric energy is produced almost exclusively from hydropower (≈ 60%), and nuclear fission power (≈ 40%) [3]. Consequently, the two big and three old and smaller nuclear power plants contribute only 10% to the Swiss energy mix.

Similar basic energy numbers can be found on the Internet at the IEA website [4] and at many other websites. As fossil fuel resources, and especially oil and gas, are not renewable, it is obvious that the world-wide energy mix of today is totally unsustainable.

While it is generally accepted that fossil fuels will not last forever, the energy situation is mainly discussed in relation to its effects on global warming. This is reflected in various high-level meetings, where climate change and other side effects of our energy use are on the agenda of world-wide policy makers. Even though the recent price explosions for crude oil have resulted in some policy changes, the serious consequences of limited oil and gas resources are rarely discussed. If addressed at all, one finds that they are discussed under the more ambiguous heading of "energy security."

Perhaps disillusioned by the official politically correct main stream arguments, many people have started to investigate the resource limitations, often under the title "peak oil and gas" and "peak everything." These problems and the need to react are now discussed at many levels, and plenty of details can be found at web sites such as the "oil drum," the "energy bulletin," and many others [5]. Those who have accepted that the situation with our use of fossil fuels is unsustainable suggest and support, in order to prevent wars, chaos, and collapse, mostly a mixture of the following three sometimes orthogonal evolutionary directions:

- the nuclear energy option;
- the all renewable energy option, based dominantly on the transformation of solar and wind energy;
- the energy reduction option, which stands for some efficiency improvements combined with an overall coordinated reduction of consumerism. Consequently, economic activities will slow down and "we" all will have to live simpler, perhaps still satisfying, lifestyles.

In this report, we shed some light on the nuclear energy option and its limitations. This analysis is split into four parts: (I) the nuclear reality of today and its short term perspectives; (II) the situation concerning secondary uranium resources; (III) the existing data about "known" exploitable uranium resources; and (IV) status and perspectives of fast breeder reactors (fourth generation reactors) and why commercial fusion reactors will always be 50 years away.

We believe that a comprehensive discussion of nuclear energy must also address problems related to (1) the real and imagined dangers of nuclear energy relative to other energy forms; (2) nuclear weapon proliferation, and (3) the accumulated nuclear waste. Yet in this series of articles, we shall not enter into any details concerning these important issues and instead refer the interested reader to the extensive literature dealing with them [6].

In this first article, nuclear energy and its place in today's world energy mix are reviewed. As significant new constructions in the nuclear power cycle, including uranium mines, enrichment facilities, and power plants, require at least a 5-10 year construction time, the maximum possible contribution of the nuclear power sector up until almost 2020 is already known and presented in this report.

It should become clear from the facts presented in the following sections of this article that the nuclear energy situation is far from being in the often claimed "nuclear renaissance phase." In fact, even without considering the impact of the 2008/9 world financial chaos, it seems already now very difficult to stop the slow nuclear phase-out, with an annual decrease of about 1%, that has been observed during the past few years.

## Energy from nuclear fission: past, present and the next 10 years

Humanity began to understand the laws of physics that describe nuclear energy with its enormous energy density about 100 years ago, when a new form of very energetic radiation from heavy elements, like uranium, was discovered. It became quickly evident that many applications were waiting to be discovered and used. Among them, we learnt to build the "final weapon of mass destruction" and found a way to produce commercial energy from nuclear fission.

In 1938, O. Hahn and F. Strassner studied the neutron bombardment of uranium observing some lighter elements. Within weeks, L. Meitner and O. Frisch could explain the reaction as the fission of uranium atoms into two lighter atoms. Today we know that, on average, 2-3 neutrons and a large amount of energy are liberated in this reaction. This observation opened the road to a controlled chain reaction using the neutrons emitted from one fission reaction to fission further uranium atoms. Such a chain reaction with a power of 2 Watt was first achieved by E. Fermi and his team in 1942. Only three years later, the world saw the explosions of two fission bombs over Hiroshima and Nagasaki that killed 150,000 people instantaneously.

The civilian use of nuclear fission energy, i.e., the nuclear energy age, began during the 1950s with the hope that this would lead mankind to an almost unlimited future energy supply. This idea came from the fact that the fission of 1 kg of uranium liberates about the same amount of energy as 1,000,000 kg of coal. Even if only the U235 component of natural uranium, which contains the two isotopes U238 (99.29%) and U235 (0.71%), can be used, one still finds that 1 kg of natural uranium contains energy equivalent of more than 10,000 kg of coal. Thus even a "useless" rock, containing perhaps only 0.01% of uranium, i.e., 0.1 kg of uranium per ton, could in theory liberate more energy than 1 kg of coal.

The necessary chain reaction to liberate nuclear fission energy is known to be possible if, on average, more than one neutron is emitted for every fission reaction. This is essentially possible only with two uranium isotopes, U235 and U233, and with the plutonium isotope Pu239, where, on average, 2-3 neutrons are emitted per fission reaction. Among them, only U235 exists naturally in sizable quantities.

The fission of these heavy elements is induced usually by a bombardment with moderated (slowed down) neutrons. If these extra neutrons are used efficiently for new fission reactions, a chain reaction, either controlled (in a reactor) or uncontrolled (in a bomb) can be started. As only one neutron is required to keep the controlled chain reaction going, the other neutrons can be used to transform the non-fissionable U238 and Thorium 232 isotopes under neutron absorption and subsequent decays into the fissionable isotopes Pu239 and U233. This neutron absorption process can be used to breed (produce) fissionable material. Already in the existing reactors, often called "once through" reactors, up to 1/3 of the produced power comes from the fission of Pu239 produced from the above U238 transformation.

A more complicated technological challenge poses the *Fast Breeder Reactor (FBR)*. This reactor is operated in a chain reaction mode using the prompt energetic (fast) fission neutrons. Theoretically, the amount of fissionable material can be increased with fast breeders by a large factor. So far, prototype commercial FBRs were not a great success for energy production [7]. More details can be found in the "Generation IV" nuclear power plant road map [8]. In this document, written by scientists from all larger nuclear energy countries, it is stated that at least 20 years of intense research and development are required before the breeder option can be considered as a real alternative to the existing standard nuclear reactors. More details about the status and prospects of FBRs will be presented in the fourth and final article in this series.

## Nuclear fission power today

Today, about 30 countries on our planet operate commercial nuclear fission power plants. During 2008, these power plants provided together 2601 TWhe [9]. "TWh" stands for Terra Watt hours or $10^{12}$ Wh and "e" stands for electric energy. The power of a standard nuclear power plant is usually given in units of GW or $10^9$ W. If a 1 GW reactor is operated with 85% efficiency over one year, about 7.5 TWhe of electricity are produced.

The amount of nuclear electricity produced in 2008 is 2.1% below that of the record year 2006 where all nuclear power plants together produced 2658 TWhe. As a consequence of the ever increasing electric energy demand, the contribution from nuclear fission energy to the total amount of produced electric energy has decreased from 18% in 1993 to 14% in 2008. Roughly 16% of the world energy end use comes from electric energy [2]. Multiplying 14% by 16%, one finds that nuclear energy contributes now less than 2.5% to the world's end energy mix.

The true nuclear energy contribution is about three times smaller than the percentage stated in most reviews of the world energy situation. The IEA and other agencies convert various sources of energy into a so-called "primary energy equivalent." In order to do so, the produced thermal energy is used for the statistics, and nuclear electric energy is multiplied roughly by a factor of three.

However, this approach is somewhat misleading as it is unclear how hydropower, where no thermal waste heat is produced, should be used in comparison. Furthermore, hydropower and gas-fired power plants provide electric energy on demand. In contrast, an efficient operation of nuclear power plants requires their operation with little interruptions at 100% capacity. As a result, nuclear power plants produce the so-called base load for the electric grid, whereas hydro and gas-fired power plants are used to satisfy peak load needs.

A fairer comparison would thus give the electric energy produced from hydropower a much higher quality factor than the one from nuclear fission power. Another problem with the primary energy accounting is related to the efficiency of nuclear power plants, which, on average, have a thermal-to-electric energy conversion factor of 33%, much lower than modern fossil fuel power plants, where efficiency factors of 50% and more can be reached. In addition, the waste heat from nuclear power plants is of lower temperature than that from gas-fired power plants. Consequently, the usage of waste heat from today's nuclear power plants is much less efficient and therefore essentially wasted to the environment. We thus find it more logical to measure the contribution from nuclear fission energy to the world end energy mix.

According to the IAEA database [10], nuclear electric energy comes currently from 436 nuclear fission reactors with an electric power capacity of about 370 GWe. The average age of these reactors is already about 25 years, and 130 reactors with a capacity of more than 90 GWe have an age between 30 and 40 years. A large fraction of those reactors will probably be decommissioned during the coming 5 to 10 years. The two oldest relatively small commercial reactors of 0.217 GWe each, have an age of 41 and 42 years and are expected to be shut down by the end of 2010 [11].

In contrast to the often repeated statement that the world is in a phase of a "nuclear renaissance," the data show a very different picture. Since the beginning of 2008, one reactor in Slovakia and two of the older reactors in Japan were shut down permanently, whereas not a single new reactor was completed. In fact, the year 2008 marks the first year since 1968, when not a single new reactor was connected to the electric grid. During the past 10-15 years, about 3-5 new nuclear power plants per year were connected to the electric grid on average, and an equivalent number of smaller and older reactors were decommissioned.

Pursuant to the IAEA data base [10], 48 reactors are currently under construction, and according to the WNA data base, roughly 10 reactors per year will be completed, on average, during the coming 5-10 years [12]. While the connection of about 10 reactors per year would indicate a substantial increase compared to the past 15 years, this number is far lower than 25 years ago, when 33 new nuclear reactors were started up each year.

If one assumes a normal reactor construction time of 5-10 years, one could imagine that all these 48 reactors might be operational between 2015 to 2020. If they can be operated as efficiently as the existing reactors, these new nuclear power plants will contribute at most about 300 TWhe per year of additional electric energy, resulting for the years 2015-2020 in a total nuclear energy production of no more than 2900 TWhe.

However, if one takes the average retirement age for the so far closed 122 reactors as a guideline, one can expect that up to 100 older smaller reactors will be decommissioned during the next 10 years. Combining these two pieces of information, it seems rather unlikely that even a net increase of the world-wide fission-produced electric energy is possible by 2015. In contrast, if one uses the annual decline of almost 1% observed during the last years as a base, a production of 2350 TWhe may be expected for the year 2015.

Consequently, one can predict for 2015, ignoring other limiting factors, that the total contribution from nuclear power plants will remain at best close to the current level.

Those interested in following the nuclear evolution during the coming months and years can compare the planned and real start-up dates summarized in a recent WNA reference document [12]. According to this WNA data base, it is planned that 7 and 8 new reactors will be connected to the grid during the remaining months of 2009 and 2010, respectively. It seems that at least the 2009 expectations are already now highly unrealistic.

**Requirements of natural uranium equivalent**

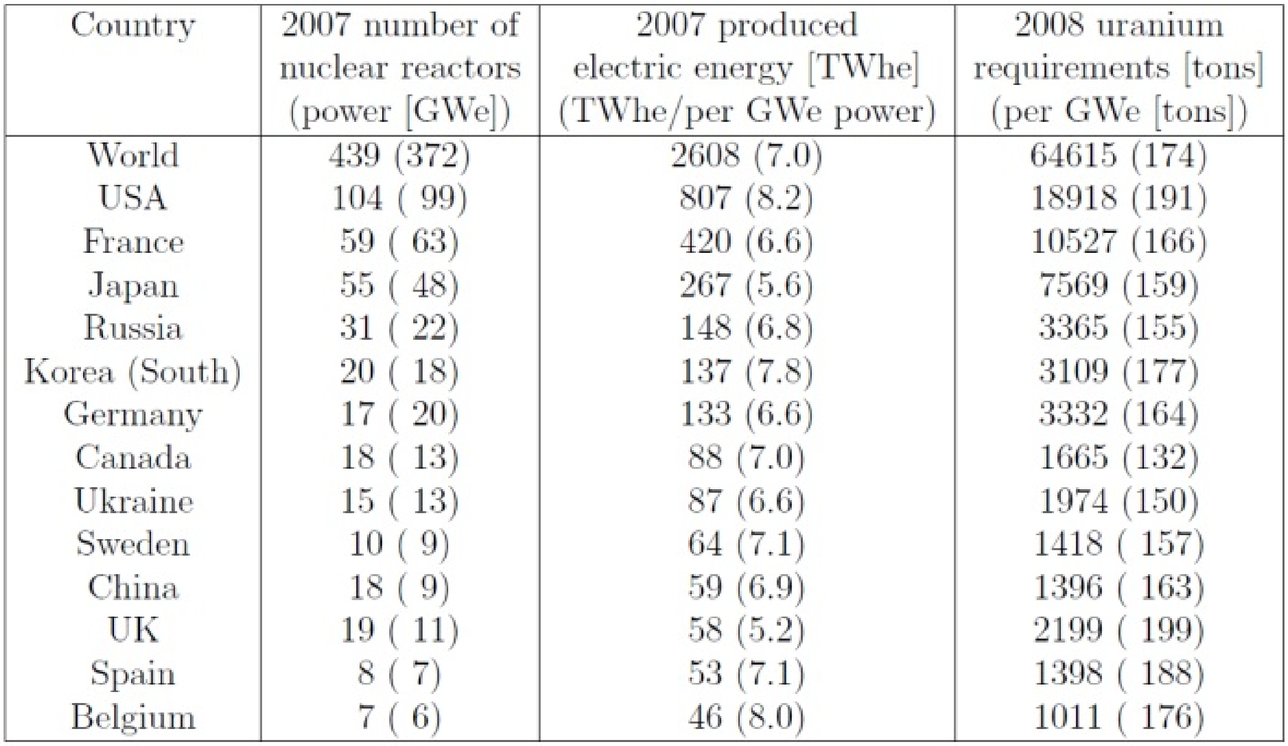
In the previous section, we have presented how the long construction times for new nuclear power plants and the existing age structure of nuclear power plants constrain the evolution of nuclear power during the next 5-10 years. We will now investigate the nuclear fuel supply situation.

Current nuclear reactors have, for several reasons, a relatively low thermal efficiency of about 33%. To operate a 1 GWe power plant, one finds that U235 or Pu239 isotopes have to be fissioned at a rate of roughly $10^{20}$ fissions/sec (about 0.05 grams/second). Knowing that the U235 isotope makes up only 0.71% of natural uranium, one finds that about 6.5 gram of natural uranium equivalent are required per second to operate a 1 GWe nuclear reactor. Multiplying this amount with the number of seconds per year, one finds that 170 tons of natural uranium equivalent per year are needed to operate a 1 GWe power plant. Therefore, about 65,000 tons of natural uranium equivalent per year are needed to operate the existing 370 GWe nuclear capacity. It is generally believed that (1) this amount of uranium can easily be obtained from the existing mines combined with secondary resources; (2) it will be easy to extract a sufficient amount of uranium from new mines in the near future; and (3) no nuclear fuel shortages should be expected for the coming years.

However as will be shown below and in Part II of this review, the situation with uranium extraction from the known mines and with the secondary resources during the coming 5-10 years appears to be much more critical than generally believed. Before we present these data, a few more details about the usage of nuclear fuel might be helpful to understand the current uranium supply situation and how it will constrain the evolution of nuclear power during the coming 5-10 years.

Nuclear reactors produce energy from the fission of either uranium U235 or plutonium Pu239, which is one of the secondary sources of nuclear fuel. To simplify the discussion, we always use the natural uranium equivalent in the following. As has been explained above, the amount of fissile material required to operate a 1 GWe nuclear power plant for one year, e.g. assuming one annual refilling, is about 165-180 tons of natural uranium equivalent per year. In practice, the normal operation of most reactors requires a few weeks of annual shutdown in order to replace about 1/4 of the used up uranium fuel rods. Fresh reactor fuel rods contain a mixture of the fissile isotopes U235 or Pu239 component enriched to 3-4% and U238. During the few years of operation, the U235 content will be reduced to roughly 1%. At the same time due to neutron capture and subsequentβ decays, some U238 is transformed into Pu239. During the reactor operation, Pu239 increases to something close to 1% and contributes on average up to 30% of the produced fission energy. Once the concentration of fissionable material in the fuel rods is reduced well below 2%, new fuel rods are usually required. The first uranium load, which brings a new 1 GWe reactor to nominal power, is about 500 tons of natural uranium equivalent.

Some important statistics about nuclear power plants in different countries, their electric energy production in 2007, and the corresponding uranium requirements, extracted from the Red Book data base of the IAEA and the NEA [14] and from the WNA [13], are summarized below.



| Country | 2007 number of nuclear reactors (power [GWe]) | 2007 produced electric energy [TWhe] (TWhe/per GWe power) | 2008 uranium requirements [tons] (per GWe [tons]) |
|---|---|---|---|
| World | 439 (372) | 2608 (7.0) | 64615 (174) |
| USA | 104 ( 99) | 807 (8.2) | 18918 (191) |
| France | 59 ( 63) | 420 (6.6) | 10527 (166) |
| Japan | 55 ( 48) | 267 (5.6) | 7569 (159) |
| Russia | 31 ( 22) | 148 (6.8) | 3365 (155) |
| Korea (South) | 20 ( 18) | 137 (7.8) | 3109 (177) |
| Germany | 17 ( 20) | 133 (6.6) | 3332 (164) |
| Canada | 18 ( 13) | 88 (7.0) | 1665 (132) |
| Ukraine | 15 ( 13) | 87 (6.6) | 1974 (150) |
| Sweden | 10 ( 9) | 64 (7.1) | 1418 ( 157) |
| China | 18 ( 9) | 59 (6.9) | 1396 ( 163) |
| UK | 19 ( 11) | 58 (5.2) | 2199 ( 199) |
| Spain | 8 ( 7) | 53 (7.1) | 1398 ( 188) |
| Belgium | 7 ( 6) | 46 (8.0) | 1011 ( 176) |

The second column gives the number of reactors per country and in parantheses the corresponding electric power. The third column gives the total amount of electric energy produced in 2007. The number in parantheses indicates the average number of TWh produced per installed GWe power, which is an indication of how efficiently the nuclear power plants were operated in 2007. A non-negligible number of reactors is always on some kind of long-term technical shut-down. A typical example is the result of the 2007 earthquake in Japan, where some 8 GWe nuclear power plants were damaged and operation has not resumed yet after two years. The number in the fourth column shows the natural uranium equivalent requirements for 2008. The number in parantheses gives the average uranium requirements per GWe installed power for the world and the different countries.

Since about 15 years, only about 2/3 of the annual uranium requirements, i.e., between 31,000 and 44,000 tons, are extracted from the world-wide mining industry. This quantity is much smaller than the mining capacity, which for example in 2007 was, according to the Red Book, 54,000-57,000 tons [15].

The difference between the required and the extracted uranium in 2007 was about 23,000 tons. This is about the same amount as extracted by the three largest uranium producing countries, Canada, Australia, and Kazakhstan, together. The missing amount of fissile material is currently satisfied with secondary resources. These are the civilian and military stocks of uranium and plutonium that were accumulated during the cold war and the so called MOX, a mixture of U235 and plutonium recycled in an expensive and technically challenging process from the used fuel rods. The tails left over from the U235 enrichment process still contain some 0.2-0.3% of U235 and are another potential source of U235. In Part II, we shall present some publicly available data on secondary resources, which provide some quantitative explanations for the alarming situation expressed (highlighted by the author) in the IAEA and NEA press declaration of June 3, 2008 [16] about the new 2007 edition of the Red Book:

> 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.

## Uranium extraction, past and present

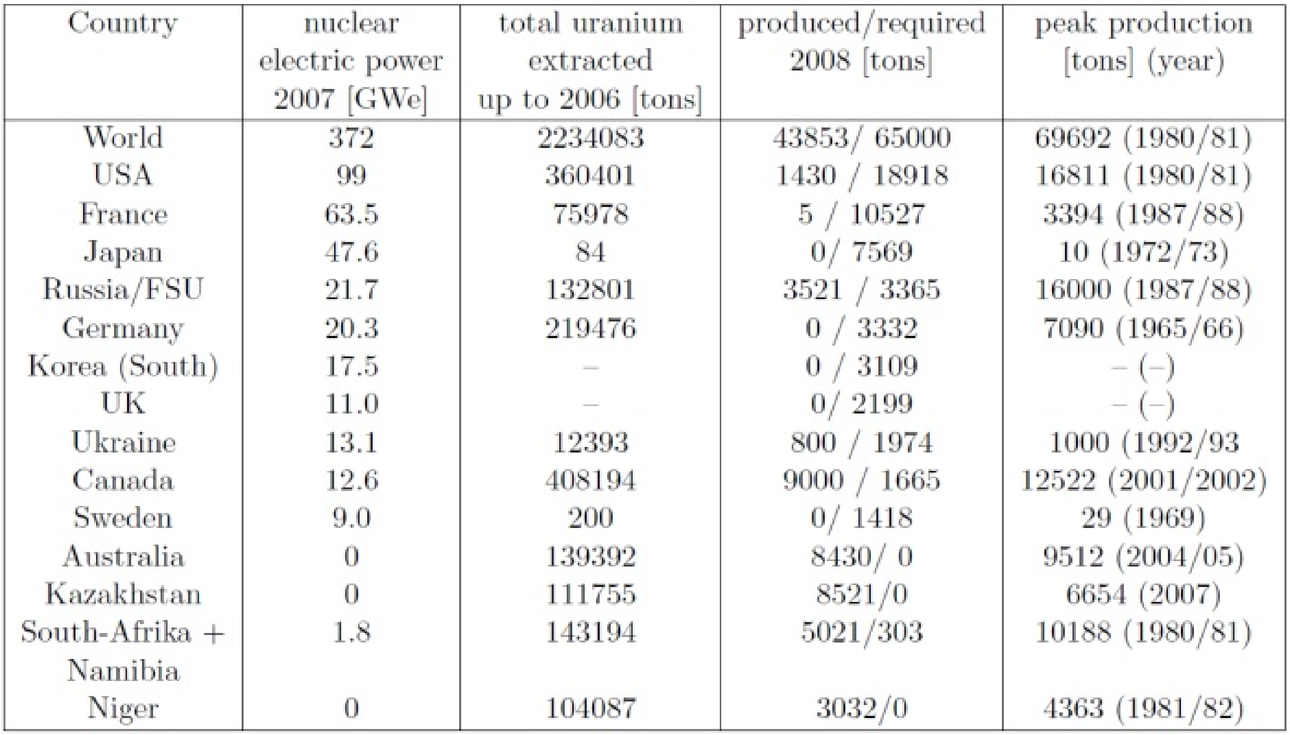
In order to understand today's uranium supply situation, it is interesting to note that many formerly rich uranium mines, especially in large uranium consuming countries, closed many years ago. This closure has happened despite that (1) the claimed goal is energy independence, and (2) uranium explorations make only minor contributions to the electricity price. Reality shows that these countries are now largely dependent on uranium imports from other countries.

Today, the ten largest uranium consumers are the United States, France, Japan, Russia, Germany, Korea (South), UK, Ukraine, Canada, and Sweden. These countries consume about 84% of the uranium needed world wide or roughly 54,000 tons of the natural uranium equivalent. This number can be compared with the uranium extracted world wide. The latest numbers from the WNA indicate that 43,930 tons of uranium were extracted in 2008 [17]. The corresponding data from the WNA and the Red Book for the previous years are 41,279 tons in 2007, 39,429 tons in 2006 and 41,702 in 2005. Somewhat remarkable is the fact that the achieved numbers are usually at least one thousand tons smaller than the short term production forecast for the next year.

Only 4 of the above 10 countries, Canada, Russia, USA, and Ukraine, are still extracting uranium in sizable quantities. Out of these four countries, only Canada, which extracted 9476 tons in 2007, produces a large amount of uranium directly for export. It is interesting to note that the existing mines in Canada seem to be in a steep decline, while upgrades and new mines are unable to compensate for this decline. During the years 2002-2005, the Canadian mines produced, on average, more than 11,000 tons per year. Since then, production fell by 5% and more per year, and only 9000 tons were produced in 2008.

The uranium mines in the above 10 largest uranium consumer countries produce only about 28% of their uranium needs, i.e., 15,400 tons in 2007 and 14,751 tons in 2008. If the two uranium exporting countries in this list are not taken into account, the remaining eight countries need to import about 95% of their requirements. For the European countries, the uranium import dependence is now almost 100% and as such much larger than their relative dependence on oil and gas imports.

The table below shows some important numbers about nuclear fission energy and present and past uranium production for the entire world and for different countries as given in the Red Book 2007 [14] and the WNA data base [18].



| Country | nuclear electric power 2007 [GWe] | total uranium extracted up to 2006 [tons] | produced/required 2008 [tons] | peak production [tons] (year) |
|---|---|---|---|---|
| World | 372 | 2234083 | 43853/ 65000 | 69692 (1980/81) |
| USA | 99 | 360401 | 1430 / 18918 | 16811 (1980/81) |
| France | 63.5 | 75978 | 5 / 10527 | 3394 (1987/88) |
| Japan | 47.6 | 84 | 0/ 7569 | 10 (1972/73) |
| Russia/FSU | 21.7 | 132801 | 3521 / 3365 | 16000 (1987/88) |
| Germany | 20.3 | 219476 | 0 / 3332 | 7090 (1965/66) |
| Korea (South) | 17.5 | – | 0 / 3109 | – (–) |
| UK | 11.0 | – | 0/ 2199 | – (–) |
| Ukraine | 13.1 | 12393 | 800 / 1974 | 1000 (1992/93 |
| Canada | 12.6 | 408194 | 9000 / 1665 | 12522 (2001/2002) |
| Sweden | 9.0 | 200 | 0/ 1418 | 29 (1969) |
| Australia | 0 | 139392 | 8430/ 0 | 9512 (2004/05) |
| Kazakhstan | 0 | 111755 | 8521/0 | 6654 (2007) |
| South-Afrika + Namibia | 1.8 | 143194 | 5021/303 | 10188 (1980/81) |
| Niger | 0 | 104087 | 3032/0 | 4363 (1981/82) |

As can be seen, (East) Germany and France have essentially stopped uranium mining, even though they used to extract large amounts of uranium from within their territory. Finally, Japan, the UK, South-Korea, and Sweden never had any substantial uranium mining of their own.

For the largest uranium consumer country, the United States, the situation is even more amazing. The internal uranium production declined from a peak of 17,000 tons per year around 1980 to a production of 1654 tons in 2007 and 1430 tons in 2008. Last year's amount does not even allow to operate 10% of their nuclear power plants. More interesting questions should come up when one considers that currently about 50% of the nuclear reactors in the USA are operated with excess military uranium stockpiles from Russia. As the bilateral contract between the USA and Russia ends in 2013 and as Russia has currently very ambitious plans to enlarge their own nuclear energy sector, it is unlikely that Russia will renew this contract in 2013. Consequently, the stability of the electric grid in the United States now depends on the friendship with their former archenemy and possibly today's and tomorrow's most important economic competitor. The dependence of USA on Russia's good will looks like an interesting problem for the next few years. These uranium data demonstrate the obvious contradiction between the goal that energy imports need to be reduced in order to achieve more energy security, as expressed by past and present US administrations, and reality.

Thus, the data demonstrate that there is nothing like uranium self-sufficiency in the United States, the European Union, Japan, and other rich countries, and that the uranium import dependence is in general much larger than for oil and gas. In fact, the data on uranium mining and the large import dependence for several large uranium consuming countries undermine strongly the widespread belief that uranium resources are plentiful and that uranium exploration and mining costs are only a minor problem for nuclear energy production.

A naive observer may conclude that the permanently repeated claims from authorities, such as from the NEA director general L. Echávarri and the IAEA deputy director Y. Sokolov in 2006 [19], that uranium resources are plentiful and sufficient to sustain the expected growth of nuclear power are either wishful thinking or assume that such statements are needed in order to reinforce the belief in a bright future for nuclear energy.

More details about uranium mining in different countries and especially their evolution during the past years and the near future needs will be presented in the next section.

### Uranium needs and production limits: the next 10 years

As we have seen in the previous section, the world nuclear power plants can reach a maximum capacity of 410 GWe by 2015. In order to achieve this number, it has to be assumed that none of current 370 GWe reactors will be decommissioned and that all plants currently under construction can be completed by 2015.

We shall now estimate how much uranium fuel can be expected for the operation of nuclear power plants around the year 2015 and whether this amount will provide a second constraint for the number of nuclear plants in operation. Such estimates are fairly reliable because the fuel needs for the reactors operating or under construction today are well known. Fuel requirements of future generation reactors are irrelevant for the next 10 years as at least 20 years of research and development are required to build them [8].

Nuclear capacity estimates and the corresponding uranium needs for the years beyond 2015 are becoming more and more speculative. For example, one needs to know what will happen with the oldest nuclear reactors and whether they can be replaced in time. Nevertheless many government agencies, like the IAEA/NEA, the IEA or the EIA from the USA government, as well as large pro-nuclear organizations like the WNA try to make forecasts at least up to the year 2030. For example the 2008 press declaration for the 2007 edition of the Red Book states [16]:

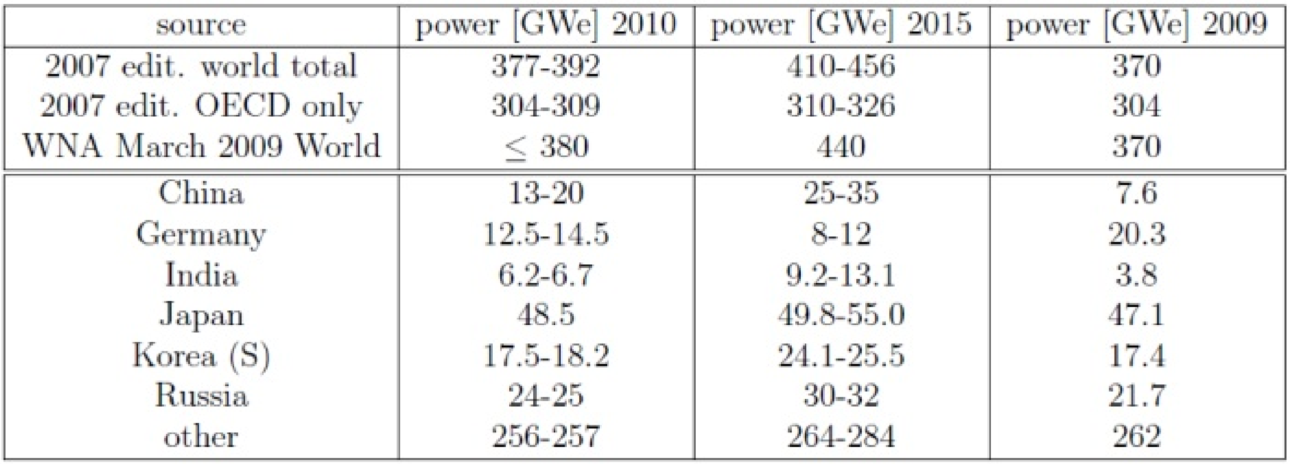
> World nuclear energy capacity is expected to grow from 372 GWe in 2007 to between 509 GWe (+38%) and 663 GWe (+80%) by 2030. To fuel this expansion, annual uranium requirements are anticipated to rise to between 94,000 tons and 122,000 tons, based on the type of reactors in use today.

More generally, three scenarios for the evolution of the yearly nuclear capacity are envisaged for the next 20 years [20]:

1. a fast growth with an increase of +2% per year;
2. a reference scenario with a 1% annual growth; and
3. a slow decline scenario with a 1% annual decrease starting in 2010.

Taking the performance from the world-wide nuclear power plants and from the uranium mines in the last few years as an indication, only scenario (3), the slow phase-out, seems to be consistent with the current data. This trend might even be strengthened by the current financial world crisis, which will make it more difficult to obtain the large commitments needed for the construction of new nuclear power plants and new uranium mines, and indeed, some construction delays for new nuclear projects have already been announced [21]. In addition, it is evident that unpredictable events such as earthquakes, accidents or wars can only result in a capacity decrease.

The uranium requirements up to at least 2015 are already well known and summarized below:



| source | power [GWe] 2010 | power [GWe] 2015 | power [GWe] 2009 |
|---|---|---|---|
| 2007 edit. world total | 377-392 | 410-456 | 370 |
| 2007 edit. OECD only | 304-309 | 310-326 | 304 |
| WNA March 2009 World | $\leq$ 380 | 440 | 370 |
| China | 13-20 | 25-35 | 7.6 |
| Germany | 12.5-14.5 | 8-12 | 20.3 |
| India | 6.2-6.7 | 9.2-13.1 | 3.8 |
| Japan | 48.5 | 49.8-55.0 | 47.1 |
| Korea (S) | 17.5-18.2 | 24.1-25.5 | 17.4 |
| Russia | 24-25 | 30-32 | 21.7 |
| other | 256-257 | 264-284 | 262 |

The nuclear power perspectives up to 2015 for different countries and the world are extracted from the Red Book 2007 [14]. The WNA numbers are taken from [12]. As quantified within the 2007 edition of the Red Book and the WNA 2009 data base, the expected increase in nuclear power plant capacity is expected to come from a few countries only. Some important aspects about these near future world-wide nuclear plans are:

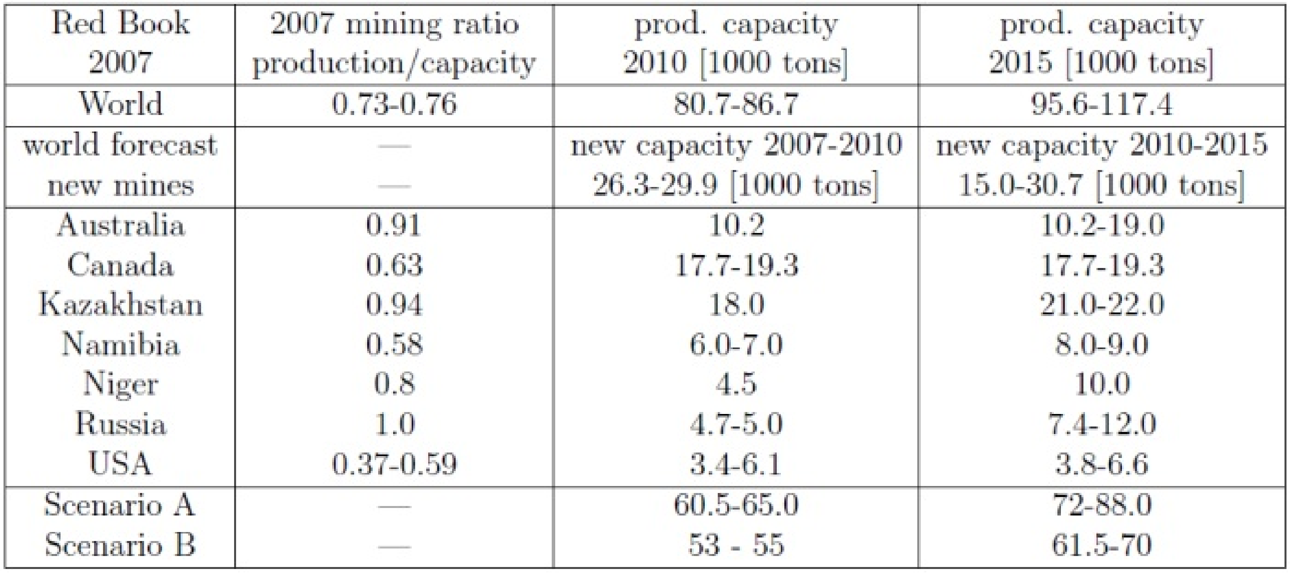
- Germany, currently the fifth largest nuclear power consumer, has indicated a definite plan for their nuclear phase-out. According to this plan, the German nuclear power capacity should be reduced from 20.3 GWe to about 11 GWe by 2015 [22].
- Very ambitious plans to complete a large number of nuclear power plants by 2015 are currently proposed by China, where the current 7.6 GWe (2007) should increase to 25-35 GWe [12]. A similar increase is planned by India, where 3.8 GWe (2007) should increase to 9.5-13.1 GWe. This can be compared with the plans from Japan, Russia, and South Korea, where their entire capacity should increase by an additional 8-10 GWe.
- The rich OECD countries are planning currently for a roughly constant nuclear capacity.

However, the high growth 2010 forecast from the IAEA/NEA Red Book 2007 is, according to the more recent March 2009 WNA numbers, already unachievable. In fact, even this WNA estimate, which assumes that during 2009 and 2010 seven (4.3 GWe) and eight (5.2 GWe) new nuclear power plants will be connected to the grid [12], seems to be totally unrealistic.

As we are interested in estimating the maximum possible contribution from nuclear power plants during the next decade, the above Red Book scenario can be used as a guideline to estimate the requirements of uranium equivalent for the coming years. In order to operate the current and future running nuclear reactors, the authors of the Red Book 2007 estimated that between 70,000-75,000 tons of uranium equivalent are required for the year 2010 and between 77,000-86,000 tons by 2015. Following the IAEA/NEA June 2008 press declaration [16], such a growth for uranium mining seems to be a serious challenge:

> 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.

Despite this and similar hidden warnings, the authors of the Red Book usually offer a rather rosy picture for the future uranium mining, as can be seen from the data summarized below:



| Red Book 2007 | 2007 mining ratio production/capacity | prod. capacity 2010 [1000 tons] | prod. capacity 2015 [1000 tons] |
|---|---|---|---|
| World | 0.73-0.76 | 80.7-86.7 | 95.6-117.4 |
| world forecast | — | new capacity 2007-2010 | new capacity 2010-2015 |
| new mines | — | 26.3-29.9 [1000 tons] | 15.0-30.7 [1000 tons] |
| Australia | 0.91 | 10.2 | 10.2-19.0 |
| Canada | 0.63 | 17.7-19.3 | 17.7-19.3 |
| Kazakhstan | 0.94 | 18.0 | 21.0-22.0 |
| Namibia | 0.58 | 6.0-7.0 | 8.0-9.0 |
| Niger | 0.8 | 4.5 | 10.0 |
| Russia | 1.0 | 4.7-5.0 | 7.4-12.0 |
| USA | 0.37-0.59 | 3.4-6.1 | 3.8-6.6 |
| Scenario A | — | 60.5-65.0 | 72-88.0 |
| Scenario B | — | 53 - 55 | 61.5-70 |

The expected uranium production capacity is given in units of 1000 tons from the Red Book for the world and for different countries for the years 2010 and 2015 [25]. The expected world-wide capacity increase between 2007 and 2010 and from 2010 to 2015 is obtained from the evolution of the total capacity. The ratio between the real production numbers for 2007 from the WNA and the uranium capacity from the Red Book are given in column 2. Scenarios A and B are rough forecasts for the maximal uranium mining for the years 2010 and 2015 based on past capacity and real mining relation. For Scenario A, it is assumed that the mining performance will be 75% of the future capacity expected according to the Red Book. For Scenario B, we assume that the existing mines in 2007 will continue an average annual production of 40,000 tons and that only 50% of the capacity forecast can become operational in time.

The predicted large increase of world-wide uranium mining almost exactly matches the requirements. However, essentially all countries exaggerate their mining capacity predictions far beyond the amount that can be reasonably extracted, as demonstrated e.g. by comparing the 2007 claimed capacity with the actually achieved uranium 2007 mining results. The numbers in the second column indicate especially large and unrealistic expectations for Canada and the USA.

For 2007, the world-wide uranium mining capacity is given as of 54,370-56,855 tons. In comparison to this capacity, the expectations from the Red book for the year 2007 were given as 43,328 tons. Uranium mining 2007 achieved 41,264 tons, about 2000 tons less than the forecast for the same year. Similarly wrong estimates were given in past Red Book editions. For example the Red Book 2003 (2005) gave capacities for the year 2003 (2005) of 49,940 tons (49,720-51,565 tons). In comparison, the achieved uranium extraction was 35,492 tons in 2003 and 41,943 tons in 2005 [23].

As if these capacity numbers, exaggerated by 20-30%, would not be troubling enough, the discrepancy between the claimed new mining capacity and the amounts that were really achieved is even more surprising. According to the Red Book 2007, the total additional capacity in 2007 compared to 2005 was estimated to be 5290 tons. The real result for 2007, a combination from older sometimes declining operating mines and new mines, was about 700 tons lower than the one achieved in 2005. For 2008, the production reached 43,930 tons, which is 2200 tones larger than in the year 2005 but still far below the increase expected already for 2007 [17].

Similar discrepancies between Red Book predictions and real extraction data can be found in previous Red Book editions. These discrepancies are, somewhat hidden, acknowledged in the latest 2007 edition. Unfortunately instead of explaining the origin of such mistakes and correcting them in order to improve the quality of the Red Book, systematic differences are simply accepted with the statement that "world production has never exceeded 89% of the reported production capability and since 2003 has varied between 75% and 84% of production capability" [24]. Further inconsistencies exist between the expected mining capacity increase and the detailed timetable given for the opening and extensions of uranium mines [25]. For example the Red Book forecast, Table 24 (page 48), assumes that between 2007 and 2010, the uranium mining capacity will increase by 26,000 to 29,900 tons. However, direct counting of the new uranium mines (page 49) results in new capacity of about 20,000 tons.

Similarly the forecast between 2010 and 2015 assumes that new mining projects should increase the capacity by another 15,000-30,000 tons. In comparison, direct counting of new uranium mines sums up at most to about 21,000 tons, about 30% below the claimed upper limit of 30,000 tons.

A critical reader of the Red Book will thus be intrigued to investigate, in which countries these capacity increases are expected. Some of these predictions, extracted from the Red Book, are shown in the table printed above. One finds that about 50% of the world-wide uranium increase between 2007 and 2010 should come from Kazakhstan. It is claimed that their production capacity will increase from 7000 tons in 2007 to 18,000 tons. Such an increase should have raised some critical reflections and comments from the authors of the Red Book, as it would put Kazakhstan on equal terms with the combined production of Canada and Australia in 2008. According to the WNA spring 2009 document, the 2010 forecast for Kazakhstan has already been reduced to 15,000 tons [26]. If one takes the latest news about a huge corruption affair concerning the uranium resources of Kazakhstan into account [27], a further drastic reduction of the 2009 and 2010 forecasts can be predicted.

Uranium mining in Canada is also far behind the Red Book expectations [28]. Not only are the real mining numbers much lower than the claimed capacities, but the existing three mines, which produce essentially 100% of the Canadian uranium, are in steep decline. The production from these three large mines (McArthur River, McClean Lake, and Rabbit Lake) declined from 11,400 tons in 2005 to 9000 tons in 2008. The previously expected 2007 start of the Cigar Lake mine, with an estimated yearly production capacity of 7000 tons, was stopped due to catastrophic flooding in late 2006. The start-up date of this mine is now delayed until at least 2012.

One may conclude that the Red Book uranium mining extrapolations are exaggerated and not based on hard facts, as one would have expected from this internationally well respected document.

Those interested in the near future nuclear energy contribution and thus uranium mining perspectives for the next 10 years should consequently not use the Red Book data directly. Instead, we might try to guess more realistic numbers by using the ratio between the 2007 mining results and the 2007 capacity as a first guess and update and improve these numbers accordingly during the next few years. Following this method, we should reduce the mining capacities by at least 20-30% in order to obtain a more meaningful forecast (Scenario A). As a result, we might predict a total uranium production of about 60,000 tons in 2010 and 72,000 tons in 2015. At least for 2010, it is already clear that the Scenario A numbers are still quite a bit too high.

For Scenario B, we used the evolution of new uranium mines in order to determine how fast new capacity can become operational. Using this procedure and the real mining data from the past few years, roughly 40,000 tons per year, and assuming that only 50% of the new mining capacities can be realized, we might predict a perhaps more realistic production of 54,000 tons in 2010, and 61,500 tons by 2015. Those numbers can be compared to the latest WNA June 2009 estimates, where a total of 49,400 tons and 74,000 tons are predicted for 2009 and 2015, respectively [29]. It seems that such professional estimations do not use much more input than a mixture of the above two simple-minded methods. Within less than one year, we shall be able to update the above scenarios using the 2009 results and improve the 2010 and 2015 forecasts accordingly.

For those interested, I am offering a bet that the 2009 and 2010 numbers will not be higher than 45,000 tons and 47,000 tons, respectively.

Taking into account that civilian secondary resources currently provide about 21,000 tons of natural uranium equivalent per year and that the civilian part of these resources will be basically exhausted within the next few years, one finds that even the optimistic WNA 2009 numbers indicate uranium fuel supply stress during the coming years. According to a recent presentation at the annual WNA September 2008 symposium from the Ux consulting (Macquarie Research commodities ) [29], about 1200 tons of uranium are missing for the 2009 demand. Furthermore, an uranium mining result below 50,000 tons/year in 2009 and beyond will result in a serious uranium shortage.

## Summary of Part I: Nuclear fission energy today

Our analysis of publicly available data from the large international and very pro-nuclear organizations, the IAEA and the WNA, show that the current evolution of nuclear fission energy is consistent with a slow nuclear phase-out. This situation is summarized by the following points:

- The overall fraction of nuclear energy to electric energy has gone down from 18% in 1993 to less than 14% in 2008. With electric energy providing roughly 16% of the world-wide energy end use, one finds overall a nuclear energy contribution of less than 2.5%.
- The number of produced TWhe of electric energy from world-wide nuclear power plants is now lower than in 2005, and it has decreased by about 2% from a maximum of 2658 TWhe in 2006 to 2601 TWhe in 2008.
- Today and world wide, 48 nuclear power plants with a capacity of about 40 GWe are under construction. Only 10% of them are being constructed within OECD countries, which host currently about 85% of the existing nuclear reactors. However, about 100 older reactors with slightly larger capacity are reaching their retirement age during the same period. It follows that even if all 48 reactors might be connected within the next 5 to 10 years to the electric grid, it will be difficult to maintain the current level of TWhe produced by nuclear energy.
- The natural uranium equivalent required to operate the 370 GWe nuclear power plants of today is roughly 65,000 tons per year. However during the past 10 years, the world-wide uranium mines extracted, on average, only about 40,000 tons of uranium per year, and the difference had to be compensated for by secondary resources. According to the data from the Red Book 2007 and the WNA, the remaining civilian uranium stocks are expected to be exhausted during the next few years. Consequently the current uranium supply situation is unsustainable.
- The urgency to increase world-wide uranium mining by a large amount is well documented in the current and past Red Book editions and related official declarations. However, the latest uranium mining data indicate that new uranium mines will not be capable to compensate for the diminishing secondary uranium resources, and that it will be difficult to fuel the existing 370 GWe. It seems that either a rather welcome but improbable further large conversion of nuclear weapons into reactor material will happen during the coming years, or fuel supply problems within the next 3-5 years will force a 10-20 GWe reduction of the operational nuclear power capacity.

We can thus conclude *Part I: Nuclear Fission Energy Today*, with the statement that publicly available official data are inconsistent with the widespread belief that the world is in a "Nuclear Energy Renaissance" phase. In reality, the data about uranium mining and the large number of aging nuclear reactors indicate that the trend of a 1% annual decrease of fission produced TWhe will continue at least up until 2015. In fact, the increasingly serious uranium supply situation might even lead to a forced nuclear shutdown of perhaps 5% of the world-wide reactors, most likely in countries without sufficient domestic uranium mining and enrichment facilities. Such a result would certainly end the widespread belief in a bright future for nuclear fission energy.

## References

[1] Statistics about the energy use in different countries can be found at the statistics page of the International Energy Agency at http://www.iea.org/Textbase/stats/index.asp.

[2] Detailed information about the electric energy production and use can be found at http://www.iea.org/Textbase/stats/prodresult.asp?PRODUCT=Electricity/Heat.

[3] Cf. for example Switzerland under [2] or the Swiss Bundesamt für Energie at http://www.bfe.admin.ch/themen/00526/00541/00542/00630/index.html?lang=de&dossier id=00765.

[4] World energy statistics are collected and published on a yearly basis by the IEA, http://www.iea.org/textbase/nppdf/free/2008/key_stats_2008.pdf; the EIA, the Energy Information Administration of the USA government, http://www.eia.doe.gov/emeu/international/contents.html; and from BP in their "Statistical Review of World Energy 2009" http://www.bp.com/productlanding.do?categoryId=6929&contentId=7044622.

[5] Some examples of government independent websites with discussions about the energy problem are The Oil Drum, http://www.theoildrum.com/; the Energy Bulletin, http://www.energybulletin.net/; and The Post Carbon Institute, http://www.postcarbon.org/.

[6] For more detailed information and further references cf. for example http://en.wikipedia.org/wiki/Nuclear_weapon and http://en.wikipedia.org/wiki/Radioactive_waste.

[7] Operation statistics, history, and known concrete plans concerning Fast Breeder Reactors (FBRs) and all other reactor types can be obtained from the IAEA PRIS data base at http://www.iaea.org/programmes/a2/ and the IAEA Fast Reactor Database at http://www.iaea.org/inisnkm/nkm/aws/frdb/index.html. Additional details can be found in the WNA Information papers http://www.world-nuclear.org/info/inf98.html.

[8] Cf. the Generation IV "Technology Roadmap" document at the GenIV International Forum http://gif.inel.gov/roadmap/.

[9] 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/info1.html; and http://www.world-nuclear.org/info/nshare.html.

[10] Past and present electric energy production data for essentially all nuclear reactors and for different countries can be found at the IAEA PRIS data base at http://www.iaea.org/programmes/a2/.

[11] For an overview of the decommissioning of nuclear facilities cf. http://www.world-nuclear.org/info/inf19.html, and for particular plans about reactor terminations in the United Kingdom cf. http://www.world-nuclear.org/info/inf84.html.

[12] For a detailed timetable about the expected grid connection of near future nuclear power plants cf. the table at the end of the WNA document "Plans For New Reactors Worldwide" at http://www.world-nuclear.org/info/inf17.html.

[13] The 2007/2008 numbers are from the WNA document http://www.world-

nuclear.org/info/reactors-jul08.html. Regular updates of this table including the 2008/2009 situation can be found at http://www.world-nuclear.org/info/reactors.html.

[14] 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."

[15] Cf. [14] Table 24 on page 48.

[16] Nuclear Energy Agency press declaration of June 3, 2008 concerning 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.

[17] Results for world-wide uranium mining extractions including the 2008 data are summarized at http://www.world-nuclear.org/info/inf23.html. Many more detailed numbers and some past estimates for the coming year(s) can be found in the different Red Book editions at the OECD book store http://www.oecdbookshop.org/oecd/display.asp?K=5KZLLSXQS6ZV&DS=Uranium-2007 and the 2006 review "Forty Years of Uranium Resources, Production and Demand in Perspective. The Red Book Retrospective."

[18] The 2008 data concerning uranium mining are from the WNA http://www.world-nuclear.org/info/inf23.html. The other numbers are extracted from the Red Book 2007 edition [14] and the from the 2006 review of the past 40 years cited under [17].

[19] Cf. for example the presentation by Luis E. Echávarri, NEA Director-General and Yuri Sokolov, International Atomic Energy Agency (IAEA) Deputy Director-General, for the new "Red Book" 2005 edition at http://www.nea.fr/html/general/press/2006/redbook/redbook.pdf.

[20] For the three scenarios up to the year 2030, cf. http://www.world-nuclear.org/sym/2005/pdf/Maeda.pdf. Some ideas about long-term nuclear growth with surprising guesses for many countries are presented by the WNA "Nuclear Century Outlook" document at http://www.world-nuclear.org/outlook/clean_energy_need.html. For example, the nuclear capacity for Germany by 2030 is estimated to be between today's 20 GWe and 50 GWe, and many more surprising and totally unrealistic numbers can be found at http://www.world-nuclear.org/outlook/nuclear_century_outlook.html.

[21] Cf. for example Nature News November 19, 2008 "Nuclear renaissance plans hit by financial crisis" at http://www.nature.com/news/2008/081119/full/456286a.html; Ameren suspends new nuclear plant plans (April 24, 2009) at http://www.world-nuclear-news.org/newsarticle.aspx?id=25101 and http://www.world-nuclear-news.org/newsarticle.aspx?id=23202 concerning a three-year delay due to various construction problems of the AREVA EPR reactor in Finland. Some more details can be found in the May 2009 IEA review: "The impacts of the financial and economic crisis on the global energy investment" and page 50/51 about its consequences for the nuclear energy sector at http://www.iea.org/textbase/Papers/2009/G8_FinCrisis_Impact.pdf.

[22] The current schedule for the nuclear phase-out of different nuclear power plants in Germany is given in http://www.world-nuclear.org/info/inf43.html.

[23] The uranium mining capacity numbers are taken from the past Red Book editions of 2003 and 2005.

[24] Red Book 2007 [14] page 86.

[25] Cf. pages 48 and 49 of the Red Book 2007 edition [14].

[26] Details about uranium mining in Kazakhstan are given under http://www.world-nuclear.org/info/inf89.html.

[27] Some details about the corruption affair in Kazakhstan can be found at http://www.world-nuclear-news.org/ENF_Response_to_Kazakh_investigation_0306092.html.

[28] The latest uranium mining result and future expectations can be found at http://www.world-nuclear.org/info/inf49.html.

[29] 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 and for the latest 2009 forecast of 49,375 tons from the WNA http://www.world-nuclear.org/info/inf23.html.