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Nuclear fissile fuels worldwide reserves

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Abstract. The paper reports on the present evaluation of uranium reserves and discusses different possibilities of the efficiency of fissile fuel use including the possibility of fuel reprocessing, MOX fuel application and breeder reactors deployment. The possibility of thorium applications and uranium extraction from law grade ores and other material streams (phosphoric acid, copper leaching solution) are discussed as well.

Key words: nuclear fuel • uranium • thorium

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Introduction

The energy crisis is a fact, the reserves of fossil fuels are almost depleted and prices are growing dramatically. Unfortunately, renewable sources will not solve the problem. Almost 100% of potential energy of rivers is acquired in many countries; biofuels grow opposition of food supplier organizations. Therefore, the application of nuclear energy is a must. The cost of producing nuclear-derived electricity is dominated by the power plant's capital cost, followed by operating and maintenance costs. Today, the cost of uranium seldom accounts for more than 2% of the cost of electricity. Therefore, if all else stays the same, doubling the price of uranium ore would result in little more than a 2% increase in the cost of nuclear-sourced electricity. For comparison, the price of coal typically constitutes between 30% and 60% of the cost of coal-sourced electricity. The price of natural gas is an even higher fraction of the cost of gas-sourced electricity [14].

Some countries of the world created the Global Nuclear Energy Partnership (GNEP), which together with the International Atomic Energy Agency (IAEA) and Atomic Energy Agency (AEA-OECD), is working on the policy towards assuring sustainable fuel supply with all aspects of non-proliferation regime [5]. The Sustainable Nuclear Energy Technology Platform of EU has presented its vision report as well [15]. The EUROATOM Supply Agency is governing the uranium fuel delivery within the European Union [3].

However, we cannot expect that uranium will be available at the present prices (or related to 2000 currency value) for longer than 100 years. Therefore, the methods of uranium recovery form depleted streams have to be searched for.

Table 1. Worldwide uranium resources (IAEA)

Reactor/fuel cycle	Years of power generation (2005) vs. identified resources	Years of power generation (2005) vs. total conventional resources	Years of power generation with conventional and unconventional sources
Once through/light water reactors	85	270	675
Recycling/fast neutron reactors	5000–6000	16,000–19,000	40,000–47,000

On the other hand, the deployment of a new generation of reactors – generation-IV fast-neutron reactors – with closed fuel cycle, leading to a better use of natural resources (typically multiplying energy production by up to 100 for the same quantity of uranium), needs to be considered. If this technology applied it is economically recoverable uranium enough to meet all power needs for thousands of years (Table 1). For the next few decades, there will be an evolutionary improvement in the performance of uranium oxide and mixed uranium oxide-plutonium oxide (MOX) LWR fuels. These improvements will be market driven to keep the cost of fuel and the resulting cost of nuclear power electricity as competitive as possible. Therefore, in relation to nuclear fuels, further R&D activities should consider development of extraction methods for uranium recovery from low grade raw materials, closed fuel cycle chemistry, MOX fuel manufacturing, thorium extraction and thorium-based fuel preparation [2, 18].

Today uranium is the only fuel supplied for nuclear reactors. However, thorium can also be utilized as a fuel for CANDU reactors or in reactors specially designed for this purpose. Thorium is reported to be about three times as abundant in the earth's crust as uranium. Neutron efficient reactors, such as CANDU, are capable of operating on a thorium fuel cycle, once they are started using a fissile material such as U-235 or Pu-239. Then, the thorium (Th-232) atom captures a neutron in the reactor to become fissile uranium (U-233), which continues the reaction. Some advanced reactor designs are likely to be able to make use of thorium on a substantial scale [17].

Uranium reserves

"Uranium 2007: Resources, Production and Demand", also known as the Red Book, estimates the identified amount of conventional uranium resources which can be mined for less than USD 130/kg to be about 5.5 million tons, up from the 4.7 million tons reported in 2005. Undiscovered resources, i.e. uranium deposits that can be expected to be found based on the geological characteristics of already discovered resources, have also risen to 10.5 million tons. This is an increase of 0.5 million tons compared to the previous edition of the report. The increases are due to both new discoveries and re-evaluations of known resources, encouraged by higher prices [12]. According to specialists, the most recent developments in the field of uranium geology, uranium exploration and exploitation technology show that sufficient resources exist to support significant growth in nuclear capacity. Already commonly known identified resources are sufficient for at least 85 years, if considering 2006 uranium requirements (of about 66,500 t U). If estimates of current usage rates are used, the identified resources would be sufficient for about 100 years of reactor supply, however the exploitation of the entire conventional resource base (some 16,872,700 t U) would increase this to 300 years, though significant exploration and development would be required to move these resources to more definitive categories. However, world uranium resources in total are considered to be much higher. Based on geological evidence and knowledge of uranium in phosphates, the study considers more than 35 million a tone is available for exploitation. The spot price of uranium has also increased fivefold since 2001, fuelling major new initiatives and investment in exploration. Worldwide exploration expenditures in 2004 totaled over US$ 130 million, an increase of almost 40% compared to 2002 and close to US$ 200 million in 2005. This can be expected to lead to further additions to the uranium resource base. A significant number of new mining projects have also been announced that could substantially boost the world's uranium production capacity.

Over the long term, recycling plutonium from reprocessed spent fuel in thermal reactors as mixed oxide fuel and the introduction of fast breeder reactors to also convert non-fissionable uranium into plutonium would increase the energy potential of today's known uranium reserves by up to 70 times, enough for more than 3000 years at today's levels of use (Table 1).

Uranium is converted into UF_6 prior to the enrichment, conversion facilities are operated in Canada, France, the United Kingdom, the United States and Russia. The conversion capacities available in Europe represent 25% of the total world capacity. The new plants including one constructed by AREVA are being built. Regarding enrichment, Urenco and Atomenergoprom are the biggest contractors. Fuel fabrication for VVER reactors is mostly manufactured by TVEL. Reprocessing of irradiated fuel continued only at the La Hague plant in France. Due to the recent increase in natural uranium prices, reprocessing is becoming economically attractive. For the first time, the United States are also looking at the possibility of reprocessing civilian spent fuel.

Thorium reserves

Thorium is found in small amounts in most rocks and soils, where it is about three times more abundant than uranium. Soil commonly contains an average of around 6 parts per million (ppm) of thorium. Thorium occurs in several minerals, the most common being the rare earth-thorium-phosphate mineral, monazite, which contains up to about 12% thorium oxide, but on average 6–7%. There are substantial deposits in several

Table 2. Concentration of uranium in different resources

Material	ppm
Ore – 2%U	20,000
Ore – 0.1%	1000
Granite	4
Sedimentary rock	2
Seawater	0.003
Phosphoric acid	40–300

countries. Thorium can also be used as a nuclear fuel through breeding to uranium-233 (U-233). Although not fissile itself, thorium-232 (Th-232) will absorb slow neutrons to produce uranium-233 (U-233), which is fissile (and long-lived). The thorium fuel cycle has some attractive features, though it is not yet in commercial use [17]. When this thorium fuel cycle is used, much less plutonium and other transuranic elements are produced, compared with uranium fuel cycles. Thorium is reported to be about three times as abundant in the earth's crust as uranium. The 2005 IAEA-NEA Red Book gives a figure of 4.5 million tons of reserves and additional resources, but points out that this excludes data from much of the world [11].

Depleted sources

Uranium is ubiquitous on the Earth. It is a metal approximately as common as tin or zinc, and it is a constituent of most rocks and even of the sea (Table 2). Uranium may be naturally found in many types of rocks including coal, shale, sandstones, granite etc. The world average uranium content in phosphate rock is estimated at 50–200 ppm. Marine phosphorite deposits contain averages of 6–120 ppm, and organic phosphorite deposits up to 600 ppm. World uranium resources in phosphate rock are not very well known; Table 3 shows approximate inventories.

The efficiency of uranium leaching determines the economic viability of treating low grade uranium deposits, and is quite sensitive to ore characteristics. The interrelationship between mineralogy, mineral liberation and the leaching behavior of uranium is not well defined. Uraninite's leaching kinetics are well studied, but relatively little leaching research has been conducted for other uranium minerals. Dissolutions higher than 90% are very difficult to achieve under the normal operating conditions employed for acid leaching of South African ores [8]. Biological methods of uranium leaching are studied as well. Native microorganisms were isolated from water samples collected from uranium mines of Jaduguda, Bhatin and Nawapahar of UCIL India. Ten fungal strains isolated in pure cultures were selected, identified and used in this study. The strains were used for *in situ* leaching of mainly oxide low grade uranium ore of Turamdih mine. The maximum recovery of 71% uranium was obtained with the strain *Cladosporium oxysporum*. The other two strains belonging to *Aspergillums flavus* and *Curvularia clavata* gave 59% and 50% of metal recovery respectively from the same ore [9].

Naturally occurring uranium typically occurs with a reducing agent such as pyrite or hydrogen sulfide, which fixes the uranium and prevents its solubilization. Thus, this naturally occurring uranium is typical insoluble, and thus stable, but is often easily solubilized by oxidation and completing with carbonate or sulfate ions. Such ions may be present in ground waters, or may be introduced by mining or other human activities. Based on the geological information, uranium is also found in copper mine rocks. Since copper ores are leached under acidic and oxidizing conditions, same conditions will also leach uranium if it is present in the copper ores. Uranium level as low as 1 ppm and as high as 40 ppm has been previously reported in copper leach solutions. Recovery of uranium from copper leach solutions can be cost-effective. Successful recovery of uranium from copper leach solutions has been reported in the literature. The world's first and the only plant to recover uranium from the said source was built and operated by the Wyoming Mineral Corporation (WMC), a subsidiary of Westinghouse, in the late seventies of the last century. This plant treated 27,000 lpm of leach solution, about 5 ppm in U_3O_8, and produced about 330 tons of U_3O_8 per year for many years before it was shut down [10].

Other source of uranium can be phosphoric acid plants. Uranium not recovered will be lost forever and, furthermore, it may be a source of pollution for soil and plants when the phosphoric fertilizer spreads to the soil. This total assumes annual production of phosphate rock of 142 million tons per year yielding 66 million tons of concentrate. Marine phosphorite deposits account for 80% of the world output of phosphate based fertilizer products, and 70% of this total is converted into wet process phosphoric acid, the widely used sulphuric acid process concentrates most of the uranium in the product stream the base for the current uranium extraction process. Phosphoric acid produced by the wet dehydrate process contains 40–300 g of uranium/ton, depending on the origin of the phosphate rocks from which it is produced. Assuming an average recoverable content of 100 ppm of uranium, this scenario would result in an annual output of 3700 t U/a. Worldwide, there are approximately 400 wet-process phosphoric acid plants in operation from which some 11,000 t U could in principle be recovered each year. A more cautious

Table 3. Approximate uranium inventories in phosphate deposits (IAEA)

Country	Million t U	Form
Morocco	6.9	Marine phosphorite
USA	1.2	– " –
Mexico	0.15	– " –
Jordan	0.1	– " –
Others	0.65	– " –
Kazakhstan and Russia	0.12	Organic phosphorite
Total	9.12	

figure of up to 3700 t U/a for the theoretically possible uranium recovery from phosphates is presented in [7]. Eight plants for the recovery of uranium from phosphoric acid have been built and operated in the United States since 1976 (Florida – 6, Louisiana – 2). Plants have also been built in Canada, Spain, Belgium, Israel, and Taiwan. Historical operating costs for the uranium recovery from phosphoric acid range from 50 to 120 US$/kg U_3O_8. These operating costs are by far higher than past uranium market prices, and most uranium recovery plants have been closed, therefore. In view of the recent increase of the uranium market price, the situation may change, again [4]. Various technologies exist to recover the uranium from the product stream [4], based on solvent extraction: DEPA-TOPO (also DEHPA-TOPO, D2EHPA-TOPO) uses di(2-ethylhexyl) phosphoric acid and trioctyl phosphine oxide as extractants (ORNL process), OPAP uses octyl phenyl acid phosphate as extractant (ORNL process), OPPA uses octyl pyro phosphoric acid as extractant (Dow process). The DEPA-TOPO process has proven to be the best technology available, according to [7]. It comprises the following steps; acid preconditioning and gunk removal, first cycle extraction and strip, rafinate post treatment, second cycle extraction, strip and uranium precipitation. Microemulsion extraction process was investigated to facilitate extraction step [13].

Uranium is dissolved in seawater in the concentration of only 3.3 ppb. Its total amount, however, reaches 4×10^{12} kg which is equivalent to the 1000 times of the mine uranium. All the world's electricity usage, 650G. We could therefore be supplied by the uranium in seawater for 7 million years. Cohen [2] considers it certain that uranium can be extracted from seawater at less than $ 2200 per kg and assumes $ 450–900 per kg the best estimate. In terms of fuel cost per MWh, it gives (uranium at $ 880 per kg – 3.75 cents, coal $ 4.26, OPEC oil $ 19.41, natural gas $ 7.2–13.6). Tamada *et al.* have developed a polymeric adsorbent which was applied for experiments *in situ*. The total amount of the adsorbed uranium was estimated by measurements on some of the adsorbent stacks to be 1 kg in terms of ammonium diuranate, $(NH_4)_2U_2O_7$ [16]. According to the OECD, uranium may be extracted from seawater using this method for about $ 300/kg-U. Tamada *et al.* [16] found that the cost varied from ¥ 15,000 to ¥ 88,000 (Yen) depending on assumptions and the lowest cost attainable now is ¥ 25,000 with 4 g-U/kg-adsorbent used in the sea area of Okinawa, with 18 repetition uses. With the May, 2008 exchange rate, this was about $ 240/kg-U.

The exploitation of unconventional uranium occurrences would require additional research and development efforts for which there is no imminent economic necessity, given the large conventional resource base and the option of reprocessing and recycling spent fuel. However, niche opportunities may be explored in greater detail in the not-so-distant future. For example, an international consortium has set out to explore the commercial extraction of uranium from coal ash from power stations located in Yunnan province, China [6]. Such tests were performed some years ago in Poland as well. The other countries are exploring their resources to be self-sufficient in uranium supply for their nuclear power plants [1].

Conclusions

1. We cannot expect that uranium will be available at the present prices (or related to 2000 currency value) for longer than 100 years.
2. Generation-IV fast-neutron reactors – with closed fuel cycle, leading to a better use of natural resources (typically multiplying energy production by up to 100 for the same quantity of uranium), needs to be considered.
3. Thorium can also be used as a nuclear fuel through breeding to uranium-233 (U-233).
4. The exploitation of unconventional uranium resources (low grade ore, phosphate rock, copper leaching solution, phosphoric acid, solid wastes) would require additional research and development efforts. However, niche opportunities may be explored in greater detail in the not-so-distant future.

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