URANIUM RESOURCES FOR THE 21^{ST} CENTURY

[1]UNDERHILL, D. H. and [2]TAUCHID, M., [1]International Atomic Energy Agency (IAEA), Vienna, Austria;
[2]IAEA (Retired), Vienna, Austria.

Summary

In 1999 about 443 nuclear reactors burned 61 600 tonnes uranium (t U) to generate about 16% of the world electricity supply. Only about 55% of the requirements were met from primary uranium production, while the remainder was met from secondary supply. While secondary supply is expected to be important over the

This paper includes the results of a new analysis of the long term uranium supply by the International Atomic Energy Agency (IAEA). To the extent possible it is based on a compilation of information from all individually known uranium deposits, as well as identified secondary supplies. It is the first long term study providing detailed projections of both primary and secondary uranium supplies. It also identifies uranium resources by: geologic deposit type, location by country, production cost, as well as estimates of the risk of political and/or environmental constraints.

Nuclear power is expected to be an important part of the world-wide energy mix at least through 2050 and, by most projections, well beyond. That is, of course, provided an adequate supply of uranium is available to sustain the nominal growth rate for nuclear power of up to 1 to 3% per year that is projected by various analysts. The objective of this study is to: evaluate uranium supply and demand relationships on an annual basis through the year 2050, determine the adequacy of supply to meet reactor requirements (demand) and characterize the level of confidence that can be placed in the projected supply. Based on these results we identify and discuss which geologic deposit types are expected to be significant sources of uranium over the next 25 years and beyond.

The following steps were taken in completing the study:

- Establish annual worldwide reactor demand expressed in metric tonnes of uranium metal (t U).
- Identify all sources of uranium potentially available to fill reactor demand.
- Determine the most likely contribution that each potential source will make to satisfying demand.
- Assess the adequacy of projected supply and broadly define market prices required to ensure supply availability.
- Identify all uranium deposits with known resources; specify resources, geologic type, known (or projected) production capability, and estimated production cost.
- Identify any deposits where potential political and/or environmental factors could prevent production.

Assessing the adequacy of uranium resources to satisfy Market-based Production requirements is the main focus of this report. Resources are categorized by confidence levels using IAEA/NEA terminology (OECD/NEA and IAEA, 2000) from the highest confidence known resources: Reasonably Assured Resources (RAR) plus Estimated Additional Resources-I (EAR-I), to lower confidence potential resources-Estimated Additional Resources-II (EAR-II) and Speculative Resources (SR). Production centres and their associated resources are also ranked by projected production costs. The order in which production centres are projected to begin operations to satisfy Market-based Production requirements is based on a combination of confidence level and cost. It has been assumed that the lowest cost producer in the highest resource confidence category will fill the first increment of demand, followed by progressively higher cost producers until annual demand is filled.

Methodology

The methodology and assumptions of this analysis follow. Uranium supply-demand projections must realistically account for a broad range of uncertainties. On the demand side of the equation, there is a wide range of opinions as to the future of nuclear power. Therefore, a prudent forecaster will recognise this uncertainty by first establishing a range of cases from High to Low to accommodate the range of possibilities from accelerated growth of nuclear power, to its gradual elimination.

Three cases of projected uranium requirements, based on a recent study by the International Institute for Applied Systems Analysis and the World Energy Council (Nakicenovic, N., Grηber, A., and McDonnell, A., 1998) are considered that cover a broad range of assumptions as to world-wide economic growth and related growth in energy and nuclear power. The cumulative uranium requirements for these demand cases through 2050 and the economic assumptions on which they are based follow:

Demand Case	Cumulative Requirements	Economic Assumptions
Low	3 390 000	Medium economic growth; phase out of nuclear power by 2100
Middle	5 394 100	Medium economic growth; sustained but modest growth for nuclear power
High	7 575 500	High economic growth; significant development for nuclear power

Uranium Supply

Similar uncertainties also characterize the supply side of the equation. One must first establish the respective roles that primary and secondary supply will likely play in satisfying uranium demand. Secondary supply is a broad term that includes the following sub-categories:

- Highly Enriched Uranium (HEU) warhead material, primarily from Russia
- Commercial and Russian inventory
- Mixed Oxide Fuel (MOX)
- Reprocessing of spent uranium fuel (Reprocessed Uranium or RepU), and
- Re-enrichment of depleted uranium (tails).

Availability of each of these sub-categories of secondary supply becomes a factor when establishing the annual contributions from total secondary supply. Newly mined and processed uranium or primary supply is divided into four categories of uranium production to reflect different levels of uncertainty and production economics:

- Supply from the Commonwealth of Independent States (CIS): Kazakhstan, Russia, Ukraine, and Uzbekistan
- National Programmes with production dedicated to domestic nuclear power programmes
- China Production, and
- Market-Based Production from all centres not included in the first 3 categories

Market-based Production includes newly mined and processed uranium from all sources excluding the other three primary production categories. The production capability of the first three primary sources is a key factor in determining the level of output required from Market-based Production to satisfy demand.

Supply scenarios based on contributions of both secondary and primary supply have been established for three demand cases: Middle, High and Low. Estimates were first made of the annual availability of secondary supply from each of the six sources. The estimates are based on available information and/or consensus opinion of the report authors. Secondary supply was then subtracted from reactor demand to determine primary supply requirements. Estimated projections were next made for the annual output from the CIS, China and National Programmes. The sum of these projections was subtracted from total primary supply requirements to establish required output from the Market-based Production category. Table I summarizes the cumulative contributions that each supply category is projected to make toward filling demand for the Middle case. While today primary production contributes around 55% of supply, it is expected to contribute about 75% of requirements through 2025 and about 89% to 2050. The balance will come from secondary supply.

Table I. Cumulative Uranium Supply and Demand (Middle case) to 2025 and 2050 (t U x 1000)

Category \ Year	2025	%	2050	%
Demand	1908.1	100	5394.1	100
HEU	249	13.1	249	4.6
Supplier Inventory *	16.7	0.9	-33.2	-0.6
Russian Inventory	39.5	2.1	39.5	0.7
MOX + REPU	134.1	7.1	286.6	5.3
Tail Reprocessing	43.4	2.3	43.4	0.8
CIS Production	271.4	14.2	551.4	10.2
National Programmes	16.5	0.9	32.5	0.6
China	31.6	1.7	66.1	1.2
Market-based Production	1105.3	57.9	4158.3	77.1

* Negative value indicates increase required to provide larger working inventory.

HEU is expected to be the second largest supply to 2020, providing about 13% of total to 2025. Over half of historical uranium production has gone into producing fissile materials for government national defence programmes. An arms race between the United States of America and the former Soviet Union resulted in the accumulation of large stockpiles of fissile materials, especially highly enriched uranium (HEU) and plutonium. As a result of arms reduction treaties between the USA and the Soviet Union and subsequently between the USA and the Russian Federation, large quantities of HEU and plutonium were declared as surplus to national defence purposes.

In the Middle demand case, secondary supply is projected to cover 42% of demand in 2000. By 2025, however, that total is projected to drop to only 6% of demand, and the percentage will continue to decline through 2050. Secondary supply is projected to supply about 11% of cumulative demand through 2050 in the Middle demand case. Primary production would supply the balance of 89%. The role of primary supply will expand as the contribution from secondary supply diminishes. Primary supply is divided into two broad categories – that which is not constrained or controlled by market conditions, such as production in the CIS, China and the small national programmes, and production that is market-based. In 2000, in the Middle demand case Market-based Production will be required to cover about 46% of demand; by 2025 that requirement will grow to 86% of demand. Market-based Production is projected to satisfy 58% and 77% respectively, of cumulative demand from 2000 to 2025 and 2050 in the Middle demand case.

Market-based Production

"Market-based Production" as used in this report consists of uranium produced at or below market costs to satisfy reactor requirements (demand) not covered by the other supply sources, including both primary and secondary supply. Total projected Market-based Production requirements through 2050 for the three (Low, Middle and High) demand cases are as follows:

Market-based Production Requirements (t U x 1000)	to 2050
Low demand case	1 918.0
Middle demand case	4 158.3
High demand case	6 404.4

A bottom up approach has been used to determine Market-based Production requirements. The previous sections describe the approach used to determine secondary supply and primary supply from the CIS, National Programmes and China. For this study, it is assumed that for reasons of economics (low cost) or policy, these supply sources will be available more or less independent of the Market-based Production category. What remains, therefore, is to determine Market-based Production in order to complete the supply-demand picture.

The first step in this process is to determine potential supply sources outside of those included in the other three primary supply categories. Three main sources were used in compiling this information: 1999 NEA-IAEA Red Book; (OECD/NEA and IAEA, 2000) International Uranium Resources Evaluation Project (IUREP) (OECD/NEA and IAEA, 1985); and the collective knowledge of the consulting specialists who contributed to this study. One of the primary objectives of this study is to assess the adequacy of world-wide resources to meet projected reactor demand. Toward that end, the IAEA/NEA resource terminology used in the Red Book has been adopted for this study. Resource categories that will be referred to are as follows (in order of decreasing confidence level): RAR; EAR-I; EAR-II and Speculative Resources (SR), also referred to as Potential Resources. It should be emphasised that even among the different resource categories, the quality of the information varies widely.

Analysis of Market-based Production

The adequacy of resources to meet demand is measured in two ways. The Market-based Production requirements for the Middle demand case are respectively, 1.105 and 4.158 million t U to 2025 and 2050. The first measure of adequacy is a comparison of resources at different confidence levels with Market-based Production requirements. The second measure takes into account the fact that all resources will not be utilized (i.e. because they will not be mined) within the study period by comparing projected production with requirements. The importance of the distinction between the two ways of measuring resource adequacy is highlighted by the following comparison based on the Middle demand case to 2050.

	RAR	RAR + EAR-I	RAR + EAR-I + EAR-II
Deficit between requirements and resources (million t U)	1.024	0.146	+2.078
Deficit between requirements and production (million t U)	1.540	0.844	0.306

This comparison indicates that relatively high confidence known resources (RAR + EAR-I) fall short of Market-based Production requirements in the Middle demand case (to 2050) by only 146 000 t U. With the addition of EAR-II, resources actually exceed requirements by about 2 million t U. However, a combination of timing when production centres will be cost-justified and the size of their resource base precludes full utilization of resources, resulting in a projected shortfall of 844 000 t U between production from known resources and Market-based Production requirements. The deficits are even more dramatic in the High demand case; in contrast, projected production from high confidence RAR will be adequate to meet all requirements in the Low demand case.

The deficits shown in the above comparison should not be construed to mean there is a shortage of uranium resources. In fact quite the opposite is true, because Speculative Resources are estimated to total 10.6 million t U. In addition, there are tens of millions of t U of high-cost unconventional resources that could be available given favourable economic incentives, namely very high uranium prices. Unconventional resources include uranium in phosphorite, black shale, lignite and coal deposits. Uranium in sea water is also included here. There are also other factors such as lowering the enrichment tails assay that could alter the supply-demand balance.

In the final analysis, there are adequate uranium resources to meet world-wide requirements for the foreseeable future. However, if the exploration effort is insufficient, or is not implemented in a timely manner, it will be necessary to rely on very high cost conventional or unconventional resources to meet demand as the lower cost known resources are exhausted. This situation would be more volatile if future uranium demand follows the High demand case of this study. The critical action will be to develop the resources in a timely manner such that they will be available to fill requirements. Secondary supply and CIS production have, during the past decade, combined to reduce Market-based Production requirements and depress market prices, which in turn has been a deterrent to exploration and new project development.

Uranium Production Costs

Another important factor in assessing resource potential or adequacy is an estimate of production costs, without which the term resource has no practical meaning. RAR production costs are based on a pre-feasibility or feasibility analysis. Table II shows the cost categories for this study.

Table II. Production Cost Categories

Cost Category	$/kg U	$/lb. U_3O_8
Low	$\leq$34	$\leq$13
Low Medium	34-$\leq$52	13-$\leq$20
High Medium	52-$\leq$78	$\geq$20-$\leq$30
High Cost	78-$\leq$130	$\geq$30-$\leq$50
Very High	>130	>50

For this analysis, once the guidelines for resource confidence levels and production cost categories were established, a preliminary list of *known deposits* and their respective resources was compiled, based on information provided by the consulting specialists, the International Uranium Resources Evaluation Project (IUREP) and Red Book data The designation “Known deposits” is emphasised to underscore the fact that these contain relatively high confidence RAR *directly attributable* to known deposits. A total of 121 known deposits and/or districts located in 31 countries are included in the analysis.

The deposits on the Study RAR list were next ranked by their relative forward production costs, combined with an estimated production capacity. Looking forward, the timing when production centres are projected to be cost-justified to begin operations will be an indirect indication of market price trends. Following is a comparison of the approximate year that production centres with different cost ranges will first be cost-justified, assuming production derived from different confidence level resources and demand cases.

Middle Demand Case	$52-78/kgU	$78-130/kgU
RAR	2019	2024
RAR + EAR-I	2021	2027
RAR + EAR- I + EAR-II	2021	2029
High Demand Case		
RAR	2013	2019
RAR + EAR-I	2015	2022
RAR + EAR- I + EAR-II	2015	2023

Based on the above comparison, under the Middle demand case and assuming availability of only known resources (RAR + EAR-I), production centres with costs exceeding $20 and $30/lb U3kgU will not be cost-justified until approximately 2021 and 2027, respectively. This indirectly indicates that the market price is not likely to rise above $20/lb. U_3O_8 before 2021, provided the deposits are brought into production consistent with the schedule foreseen in this report.

Production by Deposit-type

The IAEA guidebook to the map “World Distribution of Uranium Deposits" (IAEA, 1996) lists 582 deposits. The deposits are classified in 14 main types, namely: unconformity-related, sandstone, quartz-pebble conglomerate, vein, breccia complex (Olympic Dam), intrusive, phosphorite, collapse breccia pipe, volcanic, surficial, metasomatite, metamorphite, lignite and black shale. The main purpose of the report and the accompanying map is to show deposit distribution in relation to geology. All deposits, including those that have been mined out, are included. At the time of preparation of this report in 1995, about 19% of these deposits were in production, about 25% depleted, and nearly 56% were dormant. One of the purposes of the map and guidebook is to better evaluate the potential of each geologic formation. To translate information contained in the report into a meaningful uranium resource map, it is necessary to make a critical analysis using sound economic criteria. Production cost is clearly one of the important factors influencing the present and future market price of uranium. The supply and demand situation are other major determining factors.

Since the early 1980s the uranium market price has been declining because the market has been over-supplied with low priced uranium. Because of continuing low market prices, only production centres with resources in the low (≤$13/lb U_3O_8) and low medium (**>**$13 to ≤$20/lb U_3O_8) cost categories are expected to continue to operate over the next 10 to 15 years or more. In the year 2000 Market-based production is expected to come from only 5 uranium deposit types: unconformity related (nearly 50%), sandstone (19%), breccia complex (26%), quartz-pebble conglomerate (4%), and veins (<1%). The small amount of production from vein deposits are scheduled for closure around 2003. The last uranium by-product phosphate plant closed in 1999. Thus, almost all Market-based Production will come from only 3 uranium deposit types, with a small contribution produced as a by-product of South African gold.

This situation is expected to remain the same to around 2015. Production from other deposit types, with higher production costs, is expected to start in 2017 and beyond. It is projected that production from the intrusive, surficial (calcrete), phosphorite (by product) and collapse breccia pipe deposits may then re-start production. As the uranium price increases, additional production is expected to come from the medium cost categories of resources (from $13 to $30/lb U_3O_8), with nearly every deposit type contributing by 2025. A projection of Market-based Production by deposit type to 2025 is shown in Table III**.** In the case of CIS production during the same period, it is expected that production from the volcanic, metasomatite (albitite) and sandstone type deposits will continue around present day levels. However the importance of in-situ leach (ISL) amenable sandstone deposits is expected to increase over the period.

Conclusions

Several factors will govern the usefulness of the world's known uranium resources. Among the most important are the: growth of uranium demand, need for primary uranium, an increasing uranium market price, availability of sufficient production capacity, and the unpredictable length of the lead time between discovery and production caused by political and environmental constraints. However, there are sufficient uranium resources to meet projected demand to 2050 provided that uranium production projects are developed in a timely manner with proper planning and best operational practice so as to minimize health and environmental impacts.

Acknowledgments: This paper is based on the report "Analysis of uranium supply to 2050" to be published by the International Atomic Energy Agency. The report was prepared for the IAEA by A. Boitsov (Russia), G. Capus (France), F. Dahlkamp (Germany), S. Kidd (Uranium Institute), H. Miyada (Japan), W. Symanski (USA), I. Vera (OECD/Nuclear Energy Agency), and J. McMurray and D. Underhill (IAEA). The IAEA wishes to express its appreciation to all of those who were involved in the drafting and review and is particularly grateful to J. McMurray for his major contribution.

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Table III. Uranium production by deposit type (excluding CIS and National programmes) to 2025 (t U)

Year	2000	2005	2010	2015	2020	2025	Cumulative to 2025	Percent
Sandstone	**5380**	**3223**	**5242**	**13 159**	**14 249**	**26 239**	**286 938**	**26.1**
Unconformity Related	**13 960**	**13 720**	**19 840**	**22 523**	**20 973**	**13 473**	**490 515**	**44.6**
Qtz PebConglomerate	**1100**	**1100**	**1500**	**1500**	**1800**	**3700**	**42 857**	**3.9**
Breccia Complex	**7380**	**4800**	**3800**	**3800**	**6540**	**7310**	**143 563**	**13.1**
Vein	**200**				**1355**	**3865**	**14 102**	**1.3**
Intrusive					**3995**	**6879**	**31 120**	**2.8**
Volcanic						**6411**	**19 968**	**1.8**
Calcrete (Surficial)					**2110**	**4650**	**24 615**	**2.2**
Phosphate					**1237**	**2742**	**13 636**	**1.2**
Metasomatite						**1900**	**5599**	**0.5**
Collapse Breccia Pipe				**1031**	**1154**	**1579**	**14 611**	**1.3**
Metamorphite						**962**	**2501**	**0.2**
By-Product	**150**	**150**	**150**	**200**	**385**	**385**	**6165**	**0.6**
Demand Target	**28 170**	**22 993**	**30 532**	**42 293**	**53 798**	**80 095**	**1 098 887**	**99.8**