The Front End of the Uranium Fuel Cycle

A. Introduction

1. Uranium, the heaviest naturally occurring element in the periodic table, is an energy resource and the basic raw material for nuclear fuel. The amount of free energy contained in nuclear fuel is millions of times the amount of energy contained in fossil fuels such as coal, oil or gas, making nuclear fission a promising source of primary heat energy. Natural uranium is mildly radioactive and contains ~99.28% uranium-238 (^{238}U), ~0.71% uranium-235 (^{235}U) and traces of uranium-234 (^{234}U). The ^{235}U nucleus, when struck by a neutron, will nearly always fission, or split into two or more smaller nuclei (fission products), while releasing heat energy (Figure 1). ^{235}U is therefore termed a 'fissile isotope'. The nucleus of the more abundant isotope ^{238}U, when stuck by a neutron will absorb the neutron and become uranium-239 (^{239}U), which undergoes two consecutive ß$^-$ decays to yield plutonium-239 (^{239}Pu), which, like ^{235}U, is also a fissile isotope. The ^{238}U is therefore termed a 'fertile isotope'. Plutonium does not occur in nature but is produced in nuclear reactors from ^{238}U.

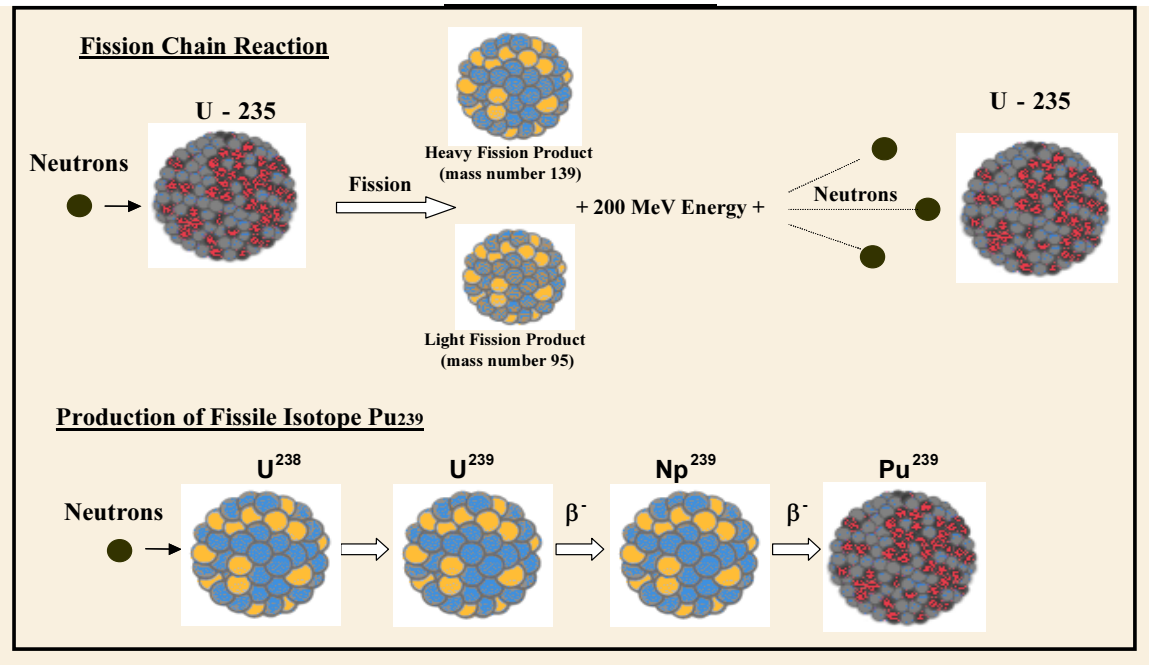

Figure 1. Fission of uranium-235 and formation of plutonium-239 from uranium-238.

2. The present generation of nuclear power reactors worldwide derive energy from the fission of ^{235}U. In some reactors, e.g. pressurized heavy water reactors (PHWRs), natural uranium can be used directly as nuclear fuel, and for most reactors, in particular light water reactors (LWRs), the concentration of ^{235}U is still low. To be used in LWR fuel uranium needs to be enriched to only 2–5% ^{235}U.

3. Most operating power reactors use uranium in the form of uranium oxide, and to a lesser extent mixed uranium plutonium oxide (MOX), cylindrical pellets as shown in the center top of Figure 2. The fuel pellets are encapsulated in long cladding tubes. For LWRs, PHWRs and the graphite moderated, light water cooled Russian RBMKs, these are made of zirconium alloys. For advanced gas-cooled reactors (AGR) they are made of stainless steel. Uranium carbide, mixed uranium plutonium carbide

and uranium nitride pellet fuels have been used in small demonstration fast reactors. A few reactors still use uranium metal fuel.

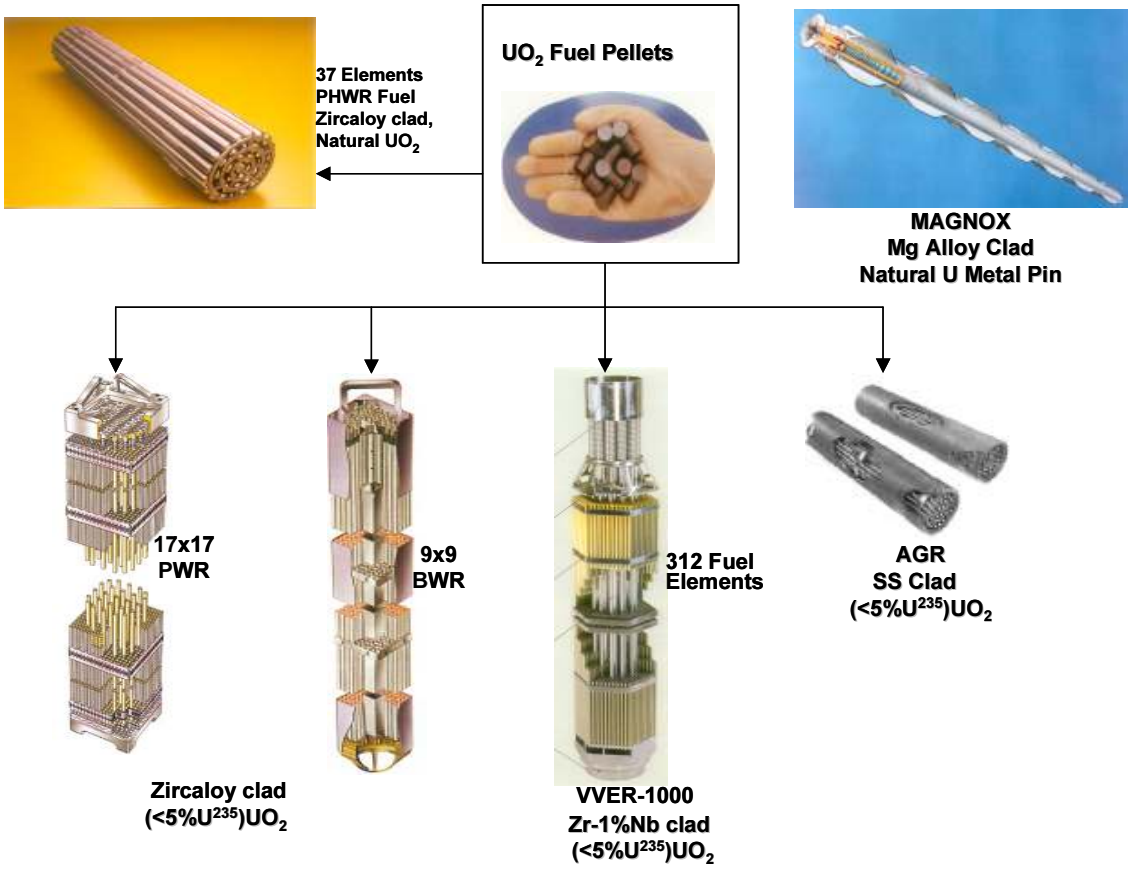

Figure 2. Natural and enriched uranium fuels for operating nuclear power reactors.

B. Uranium Resources, Geology and Minerals

4. Uranium is more plentiful than metals like antimony, beryllium, gold, mercury, silver or tungsten and is about as abundant as tin, arsenic and molybdenum. The earth's crust and oceans contain some 2.7 ppm and 0.003 ppm of uranium respectively. The major ore mineral of uranium is uraninite (basically UO_2) or pitchblende ($U_2O_5.UO_3$, better known as U_3O_8), although a range of other uranium minerals also occur naturally. The average U_3O_8 content in uranium deposits discovered to date, is between 0.03% and 20%. As with other minerals, the distribution of uranium deposits generally follows a geologically determined pattern, i.e. the age, rock type and mode of formation are the most important factors for explaining patterns of uranium deposits.

5. *Uranium resources* are broadly classified as either *conventional* or *unconventional*. Conventional resources are those that have an established history of production where uranium is either a primary product, co-product or important by-product. *Conventional resources* are further divided into four categories according to the level of confidence in their occurrence: *reasonably assured resources (RAR)*, *inferred resources*, *prognosticated resources* and *speculative resources (SR)*. The first two are collectively known as *identified resources*.

6. The category RAR includes uranium that occurs in known mineral deposits of delineated size, grade and configuration for which it is possible to specify the quantities that could be recovered, with

currently proven technologies, within given cost ranges (see below). The inferred resources category includes uranium, the occurrence of which is inferred, based on direct geological evidence, in extensions of well explored deposits or in deposits with established geological continuity. Prognosticated resources are uranium resources that are expected to occur in well-defined geological trends of known deposits, or mineralized areas with known deposits. Speculative resources refer to uranium that is thought to exist in geologically favourable, yet unexplored areas. Categories are further subdivided according to the costs of the recovered ore at the processing plant: <$40/kgU, <$80/kgU and <$130/kgU. Figure 3 shows the overall IAEA/Nuclear Energy Agency (NEA) classification scheme for uranium resources together with the amounts estimated in each category.[1]

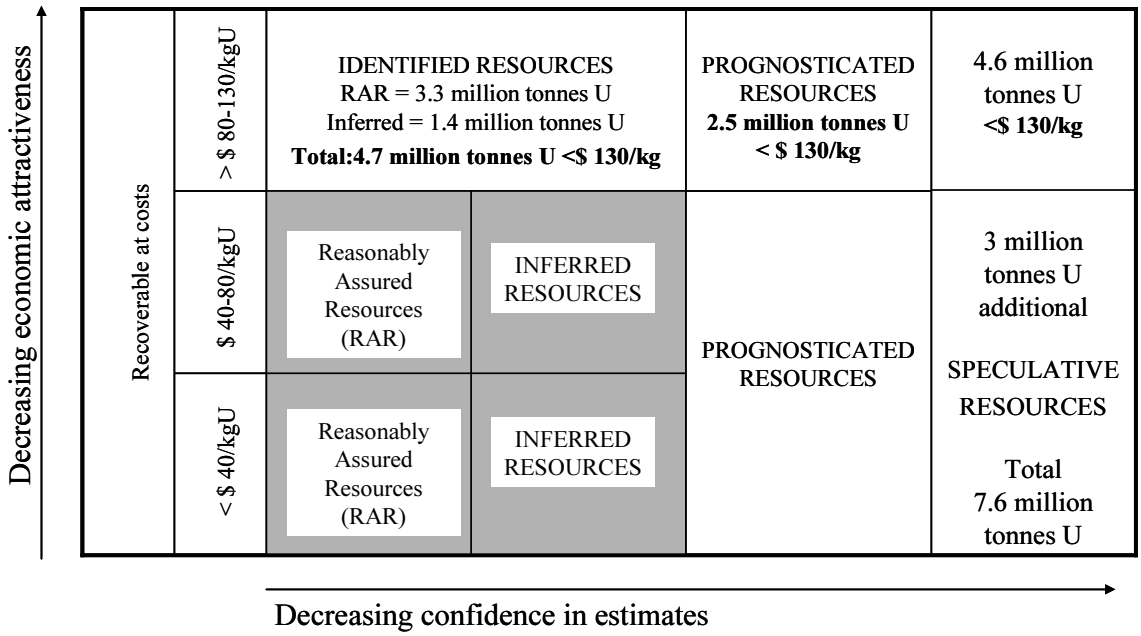

Figure 3. Classification scheme for conventional uranium resources.

7. Uranium resources classified as *unconventional*, in which uranium exists at very low grades or can only be recovered as a minor by-product, include about 22 million tonnes that occur in phosphate deposits and up to 4 000 million tonnes in seawater. The technology to recover uranium from phosphates is mature, but costs are high (~$60-100/kgU). From seawater only laboratory-scale quantities have yet been extracted, and costs are estimated to be on the order of $300/kgU.

8. Figure 4 shows the distribution of identified uranium resources around the world. Australia's resources are largest, then Kazakhstan's and Canada's. However, Canada's Cigar Lake and McArthur River are the richest uranium deposits in the world with average U_3O_8 content between 15 and 20%. For the last few years, Canada has been the world's largest uranium producer, followed by Australia. Notably, uranium is mostly located and produced in countries without nuclear power programmes and mostly consumed in countries with neither uranium resources nor production.

[1] NEA/IAEA (2006), *Uranium 2005: Resources, Production and Demand*, OECD Nuclear Energy Agency, NEA No. 6098, Paris.

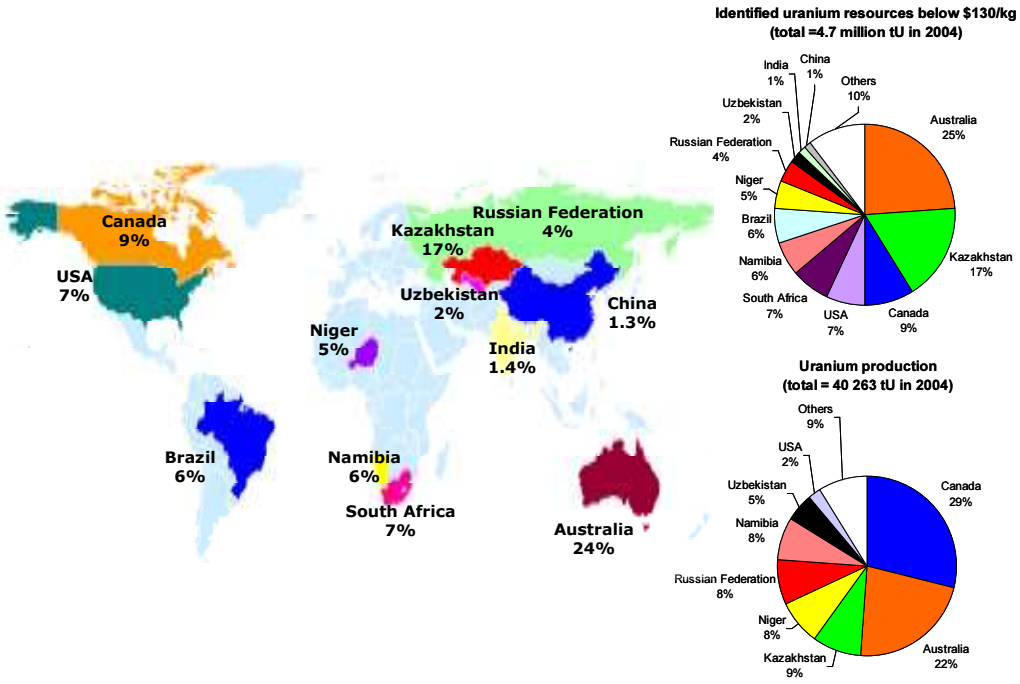

Figure 4. Distribution of identified uranium resources and uranium production in the world in 2004.

C. Uranium Supply and Demand to 2050

9. From the beginning of civilian nuclear power in the 1950s through the mid 1980s, annual production of uranium exceeded demand. Annual production of uranium peaked at 69 080 tU in 1980, gradually declined thereafter to 31 500 tU in 1994 and then rose to 40 263 tU in 2004. Since the early 1990s annual production has been consistently lower than uranium demand, and the gap has been filled by five secondary sources: stockpiles of natural uranium, stockpiles of enriched uranium, reprocessed uranium from spent fuel, MOX fuel with ^{235}U partially replaced by ^{239}Pu from reprocessed spent fuel and re-enrichment of depleted uranium tails (depleted uranium contains less than 0.7% ^{235}U).

10. The rapid global expansion in the 1960s and early 1970s drove up the price of uranium (see Figure 5) and prompted an expansion in exploration and production capacity. However, the slowdown in nuclear power's growth after 1975 and the concomitant price decline decreased the incentives for exploration and production, and, when the price reached a historic low of $18/kgU in the 1990s, led to the closure of several mines. However, as expectations have risen recently about the future expansion of nuclear power, and as secondary supplies appear likely to tighten, the uranium industry has revived with an upswing in uranium exploration, mining and milling around the world. Beginning in 2001, the price of uranium started to climb, and the spot price reached $112/kgU in May 2006.[2]

[2] The Ux Consulting Company (www.uxc.com).

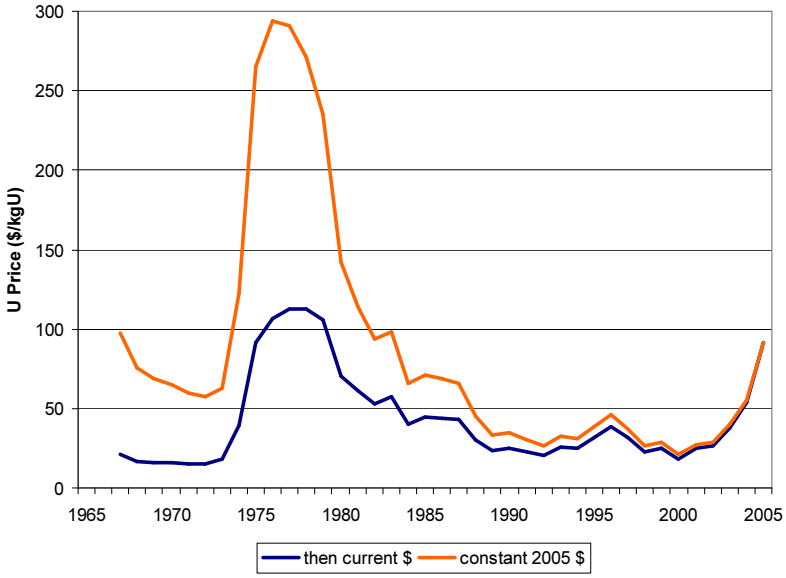

Figure 5. Uranium spot prices: 1967-2005.

11. Projecting uranium production and demand into the future is highly uncertain. To estimate the longevity of current resources, therefore, the Agency commissioned a set of uranium demand scenarios reflecting a range of assumptions about economic growth, the competitiveness of nuclear power, the availability of secondary sources, and other factors. Figure 6 shows the resulting low, high and 'reference' global projections, and compares them to the low and high projections through 2030 from Section A.2.1 of the *Nuclear Technology Review 2006*. The projections' most distinctive feature is their uncertainty. The low and high projections span an even broader range in 2030 than the low and high projections reported in Section A.2.1, and the demand projections for 2050 range from 52 000 tU (less than today's demand) to 225 000 tU, more than a factor of four higher. However, the overall conclusion drawn by the study is that the total uranium resource base can supply the projected demand up to 2050 and beyond. But the gap between uranium 'in the ground' and 'yellow cake in the can' will have to be closed by further expansion of uranium mining and milling capacities.

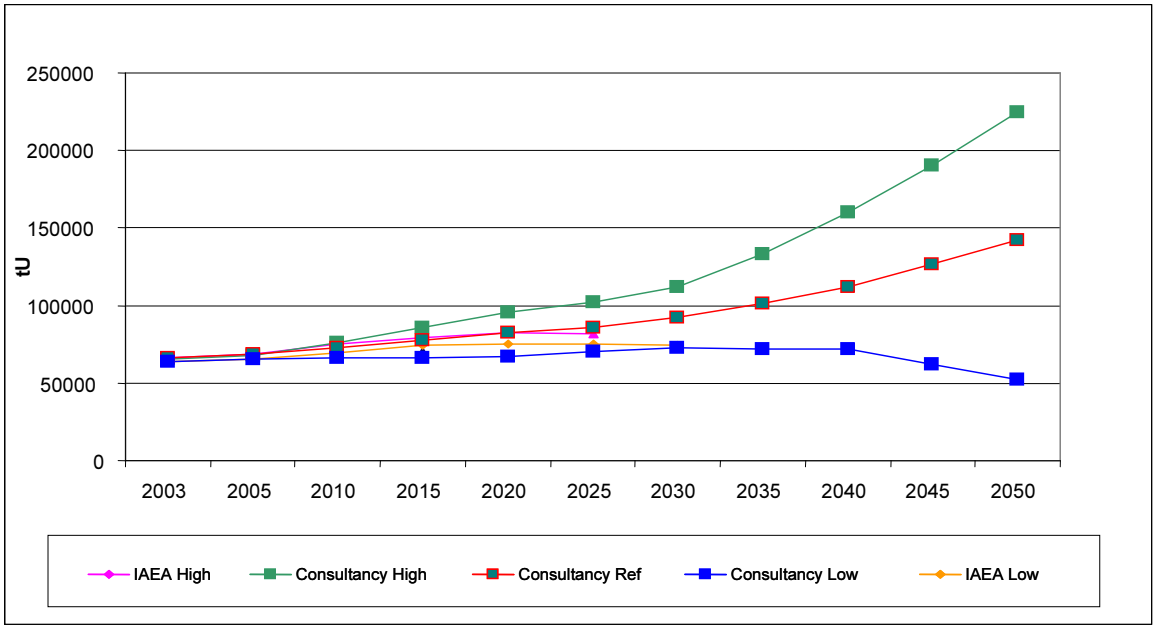

Figure 6. Uranium demand projection through 2050 (Source: IAEA).

D. The Uranium Fuel Cycle

12. Figure 7 shows the major steps in the principal variations of the nuclear fuel cycle. Uranium, as it is mined from the ground, is not directly usable as fuel for power generation. It must first go through several processing steps to transform it from ore in the ground into nuclear fuel. These steps are collectively known as the front-end of the fuel cycle. The major steps are:

- Exploration for uranium.
- Mining and milling of uranium ore to produce uranium concentrate known as 'yellow cake'.
- Purification and conversion of yellow cake into either natural UO_2 powder suitable for making PHWR fuel pellets or gaseous uranium hexafluoride (UF_6) suitable for enrichment to increase the proportion of ^{235}U.
- Enrichment, which increases the proportion of ^{235}U to 2-5%; the enriched UF_6 is subsequently converted to UO_2 powder suitable for making oxide fuel pellets for LWRs, RBMKs and AGRs.
- Fabrication of uranium dioxide fuel pellets.
- Fabrication of fuel pins made up of stacks of UO_2 fuel pellets encapsulated in cladding, which are then grouped in clusters, termed fuel assemblies.

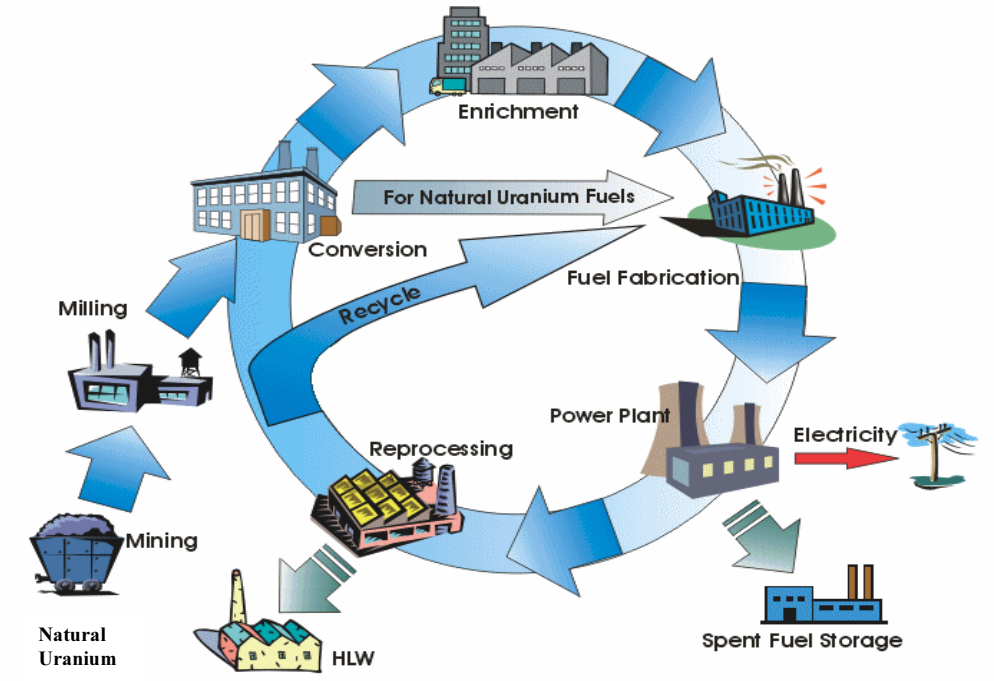

Figure 7. Major activities of nuclear fuel cycle.

D.1. Exploration for Uranium

13. Initial exploration for uranium focussed on deposits nearest the surface and easiest to discover. The highest-grade uranium deposits are, however, buried in deep rock formations. Locating and confirming such deposits requires advanced technologies like satellite imagery, geophysical surveys, multi-element geochemical analysis and computerized analyses. Prospective deposits are then subjected to detailed geological and economic evaluations, after which mining engineers develop a specific mining plan to extract the ore. Additional steps prior to implementation include environmental

impact assessments, public consultations and licensing. Altogether the time needed from the discovery of an ore body to electricity production can span decades.

D.2. Mining of Uranium

14. Uranium ore is removed from the ground in one of three ways depending on the characteristics of the deposit (Figure 8): open pit mining, conventional underground mining and in-situ leaching (ISL). Open pit mining is used to recover uranium deposits close to the surface, i.e. generally less than 100 metres depth. Deep deposits require conventional underground mining. Uranium underground mines require extra care with ventilation to control particularly radiation exposure and dust inhalation. Normally the ore is hoisted to the surface for milling. In some underground mines, however, to reduce radiation exposure from the high-grade ore, the ore is processed underground to the consistency of fine sand, diluted with water and pumped to the surface as a slurry. In-situ leaching (ISL) is a process that dissolves the uranium while still underground and then pumps the uranium-bearing solution to the surface. Depending on the composition of the ore body, weak sulphuric acid or sodium carbonate is used. The ISL process limits environmental disturbances on the surface, leaving all the surrounding rock in place while the dissolved uranium is pumped to the surface and circulated through a processing plant for extraction. By their nature ISL mines are smaller than open pit and underground mines and require correspondingly less up-front investment. ISL is the sole extraction method used in Kazakhstan and Uzbekistan and currently accounts for nearly all of US production. Table 1 lists the ten largest operating uranium mining and milling centres.

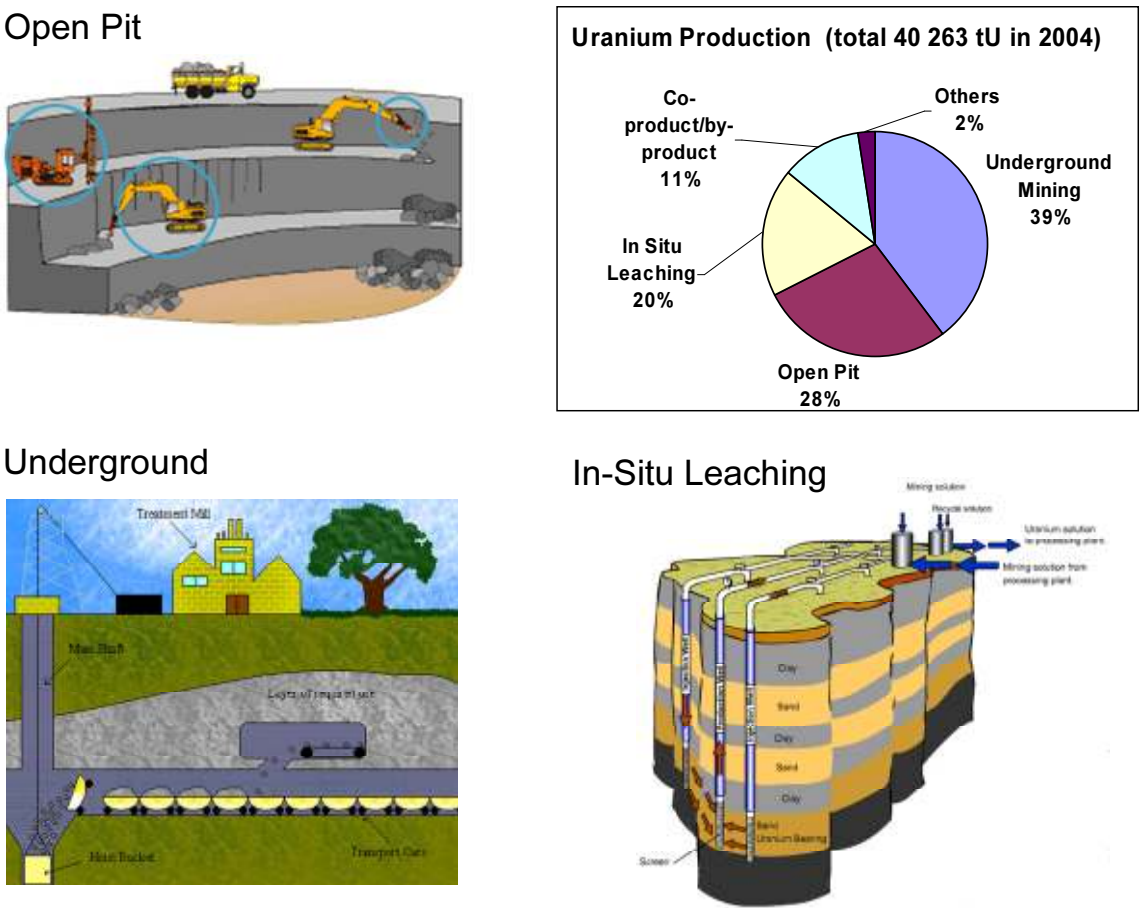

Figure 8. Major methods of uranium mining currently followed in the world.

Table 1. Large uranium mining and milling centres

Mine	Country	Main owner	Mine type
McArthur/KeyLake	Canada	Cameco	Underground
Ranger	Australia	Rio Tinto	Open pit
Rabbit Lake	Canada	Cameco	Underground
Rossing	Namibia	Rio Tinto	Open pit
Olympic Dam	Australia	WMC Resources	By-product (copper)/Underground
JSC[3] "Priagunsky"	Russia	TVEL	Underground
McClean Lake	Canada	COGEMA	Open pit
Akouta	Niger	COGEMA	Underground
Arlit	Niger	COGEMA	Open pit
Vaal Reefs	South Africa	Anglogold Ashanti	By-product (gold)/ Underground

D.3. Milling, Refining and Production of Uranium Concentrate (Yellow Cake)

15. After mining, ore is transported to a nearby mill for processing. Uranium ore is a mixture of valuable minerals and waste. Unless the ore is already in the form of a solution, as is the case with ISL, the first step is to crush the ore and treat it with acid or alkali to separate uranium from unwanted rock material. Then it is purified using solvent extraction or ion exchange process to separate the uranium. Finally, uranium concentrate, popularly known as 'yellow cake', is precipitated from the purified uranium solution, dried and baked. Yellow cake is basically U_3O_8, having a colour ranging from yellow to black.

D.4. Conversion

16. After milling, yellow cake requires further processing to convert it to uranium dioxide (UO_2) powder or uranium hexafluoride (UF_6) gas. UF_6 is the form required for subsequent enrichment. The five major conversion companies, with a combined annual conversion capacity of 62 500 tU are Rosatom (the Russian Federation), ConverDyn (USA), COMRHEX (France), CAMECO (Canada) and BNFL (UK). In addition, smaller conversion facilities operate in Argentina, Brazil, China, India and Romania.

D.5. Enrichment

17. In the enrichment process the concentration in the uranium of the isotope ^{235}U is increased. Currently there are two commercial methods of enrichment. One uses gas diffusion. The other uses centrifuges. In the gas diffusion process, ^{235}U and ^{238}U atoms are separated by feeding UF_6 in gaseous form through a series of porous walls or membranes that permit passage of the lighter $^{235}UF_6$ molecules at a faster rate than the heavier $^{238}UF_6$ molecules. In each step the uranium becomes slightly more enriched in ^{235}U. A large number of diffusion stages is required to achieve the desired level of isotope enrichment. Because this technology requires a large capital outlay for facilities and consumes large amounts of electrical energy, it is relatively expensive.

18. In the gas centrifuge process, the natural UF_6 gas is spun at high speed in a series of cylinders known as centrifuges. The rapid spinning flings the heavier ^{238}U atoms to the outside of the centrifuge, leaving the UF_6 in the centre enriched with a higher proportion of ^{235}U atoms. Gas centrifuge technology involves relatively high capital costs for the specialized equipment required, but it uses

[3] JSC = Joint Stock Company

much less electricity than does gaseous diffusion technology, and its overall advantages are leading to the gradual replacement of gas diffusion technology by centrifuge technology.

19. Looking ahead, additional advanced enrichment technologies that are currently under development include atomic vapor laser isotope separation (AVLIS) and molecular laser isotope separation (MLIS).

20. Enrichment services are sold in separative work units (SWUs). A SWU is a unit that expresses the energy required to separate ^{235}U and ^{238}U. The number of SWUs required to reach a specific amount of enriched material depends on the amount, the enrichment of the uranium feed (UF_6) at the beginning of the process, the desired final enrichment, and the concentration of ^{235}U atoms left over at the end of the process, referred to as the 'tails assay'. By varying the level of tails assay, one can find the most economical combination of UF_6 feed and SWUs required for enrichment.

21. There are currently six primary suppliers of low enriched uranium (LEU), i.e. uranium with less than 20% ^{235}U, with a total annual nameplate capacity of approximately 52 million SWUs as shown in Table 2. In additon to the primary suppliers, Argentina, Brazil, India and Pakistan have very limited enrichment capacities, totalling 300 000 SWUs.

Table 2. World enrichment capacity by technology (capacity in thousands of SWUs)

	Diffusion	Centrifuge
China (CNNC)		1 000
France (Eurodif)	10 800	
Germany (Urenco)		1 700
Japan (JNFL)		1 050
Netherlands (Urenco)		2 500
Russia (Rosatom)		20 000
UK (Urenco)		3 100
USA (USEC)	11 300	
Others		300
Total	22 100	29 650

D.6. Fuel Fabrication

22. Figure 9 summarizes the different methods that are used for manufacturing uranium oxide powder, microspheres and pellets. The first step is to prepare UO_2 powder that can be formed into high density pellets and sintered, i.e. converted from a powder to a coherent solid mass by heating. The UO_2 powder is prepared from uranium nitrate hexahydrate (UNH) or UF_6 by either wet or dry conversion processes as shown in Figure 9. The integrated dry route (IDR) uses UF_6 as a starting material and is the most common method used for preparing low enriched UO_2 powder. The two wet processes, ammonium diuranate (ADU) and ammonium uranium carbonate (AUC), can start with either UF_6 or UNH as the starting material. The IDR and ADU processes produce extremely fine (<1 micron) UO_2 powder, which is not free-flowing and therefore requires 'pre-compaction granulation' or 'roll-compaction granulation' to obtain free-flowing uranium oxide granules that can be formed into compacted 'green pellets'. The AUC process produces relatively coarse (10-20 micron) UO_2 powder that can be directly pelletized without the granulation step. The powder-pellet routes involve the handling and generation of fine uranium bearing powders and create a potential radiotoxic dust hazard. The alternative sol-gel process starts with UNH and produces dust-free and free-flowing hydrated microspheres of uranium oxide. These can then be further processed to make either high density UO_2

microspheres or soft, porous and free-flowing UO_2 microspheres. The former are used for manufacturing coated fuel particles for high temperature reactors or fuel pins by vibratory compaction.

23. The latter are suitable for direct compaction to UO_2 pellets. In general, vibratory compaction produces less dense fuel, but can be used for a more flexible range of fuel pin diameters, while pelletization produces denser fuel with a less flexible range of sizes.

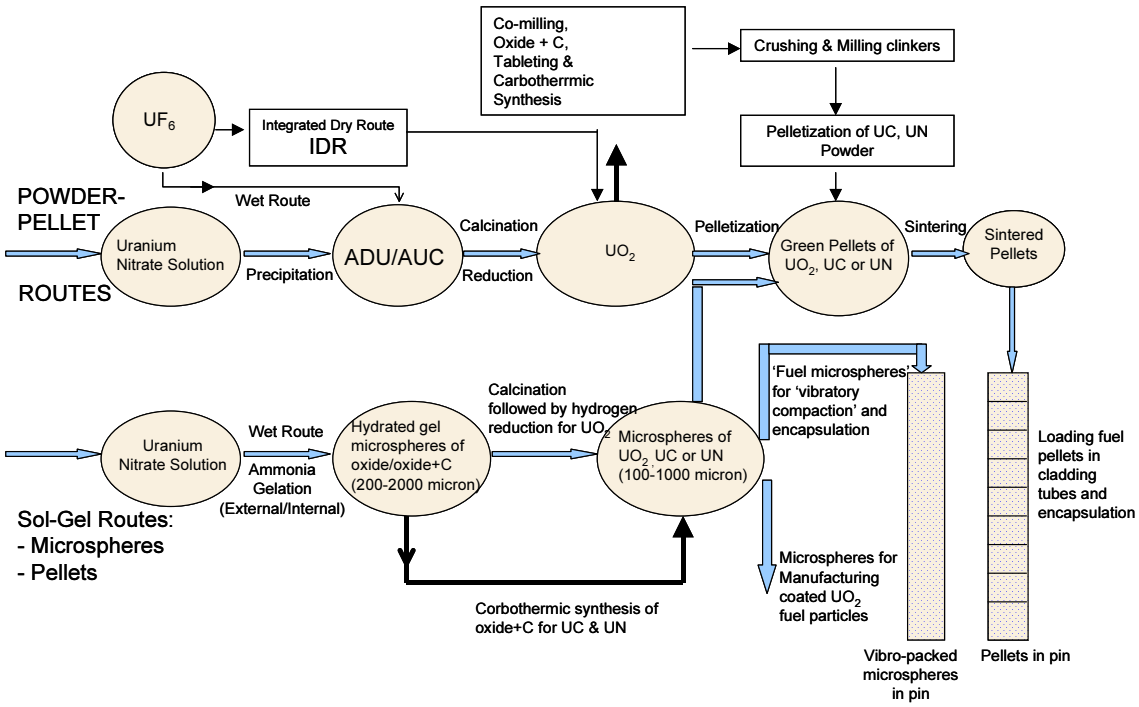

Figure 9. Different methods for manufacturing UO_2 powder, microspheres and pellets.

24. Fabrication capacity worldwide is summarized in Table 3 for LWR and RBMK fuel. For natural uranium oxide fuel for PHWRs Canada is the largest producer. It has an annual capacity of 2 700 tonnes followed by India (600 t), the Republic of Korea (400 t), China (200 t), Argentina (160 t) and Romania (150 t).

25. Current trends for both LWR and PHWR fuel are towards higher burnups (i.e. the amount of energy extracted from the fuel before it is removed from the reactor core) and toward higher performance, i.e. fewer failures. These objectives require improvements in the fuel manufacturing processes to, for example, better tailor the fuel microstructure in terms of grain size and pore structure. Additional fabrication advances are aimed at eliminating fine UO_2 powder to reduce radiotoxic dust hazards, expanding automated and remote operations to reduce exposure to radiation, reducing the number of process steps, and lowering the sintering temperature and associated costs and process losses.

Table 3. LWR fuel fabrication capacity worldwide (tonnes of heavy metal, tHM)

Country	Fabricator	Conversion	Pelletizing	Rod/Assembly
Belgium	Framatome-FBFC/Dessel		750	200
Brazil	INB/Resende	160	120	200
China	CNNC/Yibin	270	200	200
France	Framatome-FBFC/Romans	1200	1000	1000
Germany	Framatome-ANF/Lingen	650	650	650
Japan	NFI/Kumatori (PWR)		284	284
	NFI/Tokai-Mura (BWR)		200	200
	Mitsubishi Nuclear Fuel	450	440	440
	GNF-J/Kurihama (BWR)	750	750	750
Kazakhstan	ULBA/Ust Kamenogorsk	2000	2000	-
Korea, Republic of	KNFC	400	300	300
Russian Fed.	MSZ/Elekrostal	1450	1200	1200
	NCCP/Novosibirsk	250	200	400
Spain	ENUSA/Juzbado		300	300
Sweden	Westinghouse/Vasteras	600	600	400
UK	Westinghouse/Springfields	950	600	860
USA	Framatome/Richland (BWR)	1200	500	500
	Framatome/Lynchburg (PWR)		400	400
	GNF/Wilmington	1200	1200	750
	Westinghouse (Columbia)	1200	1200	1200
Total		**12730**	**12894**	**10784**

E. Concluding Remarks

26. The front-end of the uranium fuel cycle is a well established part of the nuclear industry with major operations in a number of countries around the world. The reference fuel for most reactors operating today, or foreseen to come on line in the next few decades is composed of high density uranium oxide pellets, both for LWRs, which use LEU enriched to 2-5% ^{235}U, and for PHWRs, which use natural uranium.

27. The world's identified conventional uranium resources of 4.7 million tU are adequate to fuel today's reactors for another 85 years. Exploiting the world's total conventional resources would extend the number to 270 years. With the expected growth in nuclear production a more efficient use of the uranium resource will be beneficial to ensure long-term availability. Most of the reactor types considered for the next generation of reactors (Generation IV), that will be available in 20-30 years, will increase the resource efficiency substantially. In recent years, the demand for uranium has been around 66 000 tU per year, much higher than the annual primary uranium production of approximately 40 000 tU. The gap between uranium demand and the primary supply from current mines has been bridged by secondary sources, and these are expected to play a continuing important role in the uranium market through at least till 2015. In the last few years, uranium prices have risen substantially, which, in turn has encouraged the expansion of exploration, mining and production plus an increase in conversion and enrichment capacities. Currently, there is excess UO_2 fuel fabrication capacity globally, but in light of rising expectations for global growth in nuclear power, additional fuel fabrication capacity will also be needed.