2.2 Nuclear fuel cycle

Though it is possible that power might be derived from nuclear fusion at some point in the distant future, all presently feasible methods of nuclear power generation utilize the energy released during nuclear fission, that is to say the process by which a neutron colliding with an atom causes that atom to split and, as a by-product, produces heat. With atoms known as fissile atoms, additional neutrons are released at the same time thus allowing a continuing, naturally regenerating process of fission and a source of heat. The only naturally occurring fissile material is the uranium isotope, ^{235}U, but it only occurs along with a much greater quantity of the common isotope, ^{238}U. Specifically, naturally occurring uranium contains 99.29% of ^{238}U and only 0.71% of ^{235}U (138 atoms of ^{238}U for every atom of ^{235}U). With a singular exception, these proportions are the same everywhere on earth because they date from the original creation of uranium by fusion and the similar decay of these isotopes since that time. The exception is a location in Oklo, Gabon, Africa, where, about 1.7 billion years ago, a uranium-rich mineral deposit became concentrated through sedimentation and, with the water acting as moderator (see section 2.8.1), formed a natural nuclear reactor (Gauthier-Lafaye *et al.* 1996, Meshik 2005). The reactor became subcritical when water was boiled away by the reactor heat (though it restarted during subsequent flooding). The consequence was a uranium ore deposit that contained only 0.60% or less of ^{235}U (as opposed to 0.71% elsewhere).

The nuclear fuel cycle refers to the sequence of steps in a nuclear power generation system, from the mining or acquisition of the raw ore to the refining and enrichment of that material, to its modification during power production and thence to the management of the nuclear waste. Many of the steps in a nuclear fuel cycle involve complex engineering and economics that are beyond the scope of this book (the reader could consult Knief (1992) for a comprehensive summary). However, a brief summary of commonly-envisaged fuel cycles is appropriate at this point. A basic feature of those cycles is an assay of the mass of the essential material during each step (as well as the waste). Another is the power consumption or generation during each step. One example of a nuclear fuel cycle is shown in figure 1 which presents the uranium requirements for a 1000 MW pressurized water reactor.

Since ^{235}U is the only naturally-occurring fissile material, the nuclear fuel cycle must necessarily begin with the mining and milling of uranium ore. Uranium ore is relatively common and additional recoverable resources are being discovered at a significant pace; indeed the known resources have increased by a factor of about three since 1975. Some 40% of the known recoverable resources are found in Canada and Australia while Russia and Kazakhstan hold another 21% (the highest grade uranium ore is found in northern Saskatchewan). Thorium, an alternate nuclear reactor fuel (see sections 2.11 and 2.2.1), is reputed to be about three times as abundant as uranium (WNA 2011).

Uranium is usually removed from the ore by chemical milling methods that result in the production of U_3O_8, known as yellowcake. The waste or *tailings* present some, primarily chemical disposal problems. With the exception of the

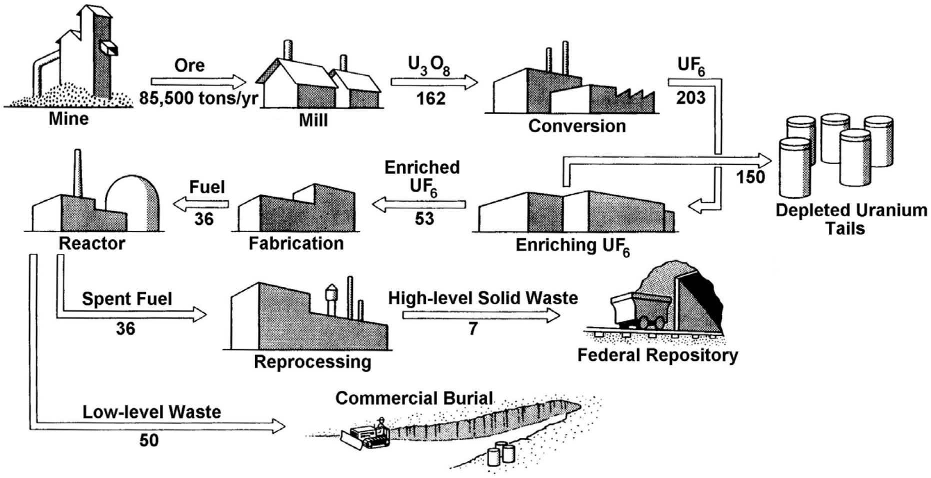

Figure 1: Uranium requirements for a typical pressurized water nuclear reactor (see section 4.3.2). The numbers refer to the number of tons of each material required per year for a 1000 MW electric power plant. From USAEC (1973).

CANDU reactor described in section 4.8, all other current reactors require the uranium to be *enriched*, a process in which the fraction of ^{235}U is increased. In preparation for enrichment, the uranium is converted to a gaseous form, namely from U_3O_8 to UF_6 in a process known as *conversion*. Several possible methods have been used to enrich the UF_6 and this requires the separation of $^{235}UF_6$ from the $^{238}UF_6$, a process that cannot be accomplished chemically since these isotopes are chemically identical. The separation must therefore be accomplished physically by recourse to the small physical differences in the molecules, for example their densities or diffusivities. The most common conversion process uses a gas centrifuge in which the heavier $^{238}UF_6$ is preferentially driven to the sides of a rapidly rotating cylinder. Another is the gaseous diffusion method in which the gas is forced through a porous filter that the $^{235}UF_6$ penetrates more readily. In either case a by-product is a waste known as the *enrichment tailings*.

Whether enriched or not the fuel must then be formed into fuel ready for loading into the reactor. In most reactors this fuel fabrication stage involves conversion to solid pellets of UO_2 or, less commonly, UC. These cylindrical pellets are then packed into long fuel rods (as described in section 4.3.4) whose material is referred to as *cladding*. The rods are then loaded into the reactor. The fuel cycle continues when the fuel rods are spent and removed from the reactor and the spent fuel is reprocessed.

However, before resuming this review with a description of the fuel changes that occur in a uranium reactor, it is appropriate to briefly digress to mention the other naturally available fuel, thorium, and its fuel cycle.