The Nuclear Fuel Cycle

by B. Rouben
Manager, Reactor Core Physics Branch
Atomic Energy of Canada, Ltd.

In this seminar we'll discuss the nuclear fuel cycle: we will cover the various phases in the use of nuclear fuel, from mining to disposal, and we will look at the different forms that nuclear fuel can take in a reactor, with specific emphasis on possible applications to CANDU reactors.

The discussion will provide opportunities to ponder multiple issues with important social impact: use of natural resources, efficiency and economy of utilization, "throw away or recycle", possible proliferation of prescribed materials, and how to deal with fuel after it's irradiated.

From Mine to Fuel

The front end of the nuclear fuel cycle is the production of nuclear fuel. The first phase is obviously the mining of uranium. Canada (Saskatchewan) has large deposits of uranium ore and is the biggest uranium producer in the world, with about 30% of the world's uranium market on its own.

The most common uranium-bearing mineral is uraninite. The uranium is separated and concentrated out of the uraninite in a mill, in a leaching process whose final product is yellowcake, U_3O_8 (70-80% by weight uranium). What remains behind is low-concentration uranium "tails".

The U_3O_8 is reduced with hydrogen to uranium-dioxide (UO_2) powder, which is pressed (compacted) into fuel pellets. The pellets are sintered (fired) to produce a hard UO_2 ceramic. After sintering, the pellets are ground to the required diameter, 12 mm for currently-used CANDU fuel. The pellet length is approximately 16 mm. A number of pellets are encased in ~50-cm-long "elements" made of zircaloy, which are then assembled into bundles with 28 or 37 elements per bundle. A 37-element bundle contains about 20 kg of uranium.

The above sequence applies to natural-uranium fuel, as used in CANDU reactors. For other reactors, the uranium must be enriched in the ^{235}U isotope. In this case the yellowcake is first converted to gaseous uranium hexafluoride, UF_6, which is then subjected to enrichment (by gaseous diffusion or centrifuge process). The enrichment process increases the manufacturing cost of nuclear fuel significantly.

Once-Through Fuel Cycle

The simplest way to use nuclear fuel in a reactor is the once-through fuel cycle: only new fuel enters the reactor, and once the fuel is used up, it is removed permanently for storage and eventual disposal.

The main energy source in natural or enriched uranium is initially fission in ^{235}U. However, while the fuel is being "burned" in the reactor, plutonium is being produced from neutron absorption in the "fertile" isotope ^{238}U. The isotopes ^{239}Pu and ^{241}Pu are both fissile, and once created, they contribute to the energy released; that is, plutonium is both created and burned *in-situ*. In fact, in CANDU, half the total energy produced originates in plutonium fission.

As the fuel is burned in CANDU, the ^{235}U is being depleted, but there is a net increase of plutonium with time. The fissile component in the fuel starts at 0.71% (the concentration of ^{235}U in natural uranium), and when the fuel is discharged the total fissile component is still 0.50% (0.23% ^{235}U and 0.27% fissile Pu). This means there is still much energy left in the irradiated fuel: it is discharged not because it is fully used-up, but because neutron-absorbing fission products have built up in the fuel and it is a net load on the system.

For typical light-water reactor fuel, the initial fissile content is 3.5% ^{235}U, while the fissile content at discharge is ~1.5% (0.9% ^{235}U and 0.6% fissile Pu). So discharged light-water-reactor fuel has more than twice the fissile content of natural uranium!

The once-through cycle is simple, but the above figures clearly demonstrate that "spent" fuel (as discharged fuel is often called) is really far from spent! Simply "throwing away" the energy in the discharged fuel is in fact extremely wasteful.

The once-through nuclear fuel cycle is therefore not compatible with the "reduce, reuse, recycle" philosophy. There are two reasons why the once-through cycle continues to be used however:

- economics: the price of natural uranium is sufficiently low to make the cost of recycling the used fuel unattractive.
- politics: some countries (the U.S.) have banned the recycling (reprocessing) of fuel for commercial power plants, in an attempt to set an example and discourage the proliferation of nuclear-weapons material (plutonium).

Alternative Fuel Cycles for CANDU

The neutron economy of CANDU reactors permits the use of natural uranium, and in addition gives great flexibility for the application of other fuels. Some of these alternative possibilities which could be applied in CANDU are described here. The idea is to extend our resources by increasing the uranium utilization, i.e., getting more energy per unit (kg) of mined uranium.

Some of the concepts described here are also applicable or sometimes already in use (to varying degrees) in other reactor types, whereas others are exclusive to CANDU.

Slightly Enriched Uranium

Slightly enriched uranium contains a greater concentration of ^{235}U than natural uranium. Fuel with ^{235}U concentrations in the range 0.9-1.2% (compared to 0.71% in natural concentration) can be used in CANDU without changes in the reactor, and with optimum uranium utilization. Light-water reactors also of course use enriched uranium, but because of the poorer neutron economy, need enrichments of about 3% and greater.

Recovered Uranium

As mentioned above, fuel discharged from light-water reactors contains about 0.9% ^{235}U. If the fuel is reprocessed so that the plutonium and uranium are separated, then the **recovered uranium** is approximately equivalent to slightly enriched uranium and could be used in CANDU. Recovered uranium is available from commercial fuel reprocessors, but is not usable as is in other reactor types since the enrichment is too low. Thus the use in CANDU would in effect reduce the amount of fuel waste from other reactors. This is a type of **synergism** between CANDU and other reactor types.

Mixed-Oxide Fuel (MOX)

If fuel is reprocessed, then the fissile plutonium is also available for use. The plutonium, in **PuO_2** form, could be mixed with "virgin" uranium oxide to make mixed-oxide (MOX) fuel to be burned in CANDU. With sufficient total enrichment, MOX fuel can also be used in light-water reactors. MOX is **already**, in fact, used in Europe, although for technical reasons it has been limited up to now to about 1/3 of the core. As mentioned above, the U.S. has foregone the use of reprocessing spent fuel, and does not burn MOX in its reactors. Once again, this fuel cycle aims at getting more total energy out of the original mined uranium. In addition, the amount of waste to be disposed of per unit of electricity produced is much reduced.

Weapons-Derived Plutonium

If MOX can be made starting from plutonium reprocessed from fuel discharged from commercial reactors, it can also be made starting with plutonium derived from weapons. The U.S. and Russia have agreed to reduce their nuclear arsenals, and as a result there are over 100 tonnes of plutonium available for draw-down from weapons. This use of military plutonium in reactors is the ultimate **swords-to-plowshares** opportunity: a useful commodity being created at the same time as a threat to world peace is significantly reduced!

DUPIC

Chemical (wet) fuel reprocessing separates the uranium and plutonium. This is considered by some as presenting a risk from the point of view of weapons-material proliferation.

The DUPIC cycle is a research project presently being carried out co-operatively by Canada and Korea. It provides an alternative to chemical reprocessing. DUPIC stands for Direct Use of PWR Fuel in CANDU. In DUPIC, “spent” PWR fuel is first mechanically decladded and then treated by a **dry** oxidation-reduction process to remove the volatile fission products. The process yields a powder, which can then be pressed into pellets again. The process does not involve chemical separation of the uranium and plutonium, and so is superior from the safeguardability point of view. This DUPIC fuel will typically have a total fissile content of about 1.5%, so cannot be used in PWRs. However, the fissile content is certainly sufficient for use in CANDU, where in fact DUPIC fuel would yield about **twice as much** energy again as was produced in the original cycle in the PWR! The ideal **synergism** between CANDU and PWR: fuel is first burned in PWR, and then, instead of being thrown away, yields another two times as much energy in CANDU. Again, the total amount of waste per unit of electricity is much reduced. The research is presently at the stage where some DUPIC fuel elements have been produced and test irradiations will be conducted in research reactors.

The Fast Breeder Reactor

Most reactors operating today are thermal reactors. However, fast (i.e., fast-neutron) reactors are also possible, and in fact prototypes have been built. While the probability of fission is much smaller at high neutron energies, the number of neutrons produced per fission is higher, and extra neutrons can be used to produce more plutonium from the fertile ^{238}U. In fact, **more fissile material can be produced than is consumed!** This is the fast breeder reactor (FBR), which creates its own fuel, and thus has the potential of extending the utilization of uranium resources from decades to **centuries**.

The Thorium Cycle

There is another fertile isotope besides ^{238}U: ^{232}Th, which, on neutron absorption and β-decay, yields ^{233}U, a fissile isotope. Thus thorium can be used to produce ^{233}U, which can then be burned just as ^{235}U or ^{239}Pu. Since there is approximately three times as much thorium as uranium in the world, this would be another way of extending our precious uranium resources.

The Back End

No matter which fuel cycle is used, there is eventually fuel to be disposed of. This is the “back end” of the fuel cycle.

Spent-Fuel Bays

Fuel which comes out of the reactor is “hot” - both temperature-hot and radioactivity-hot. The first step in dealing with the fuel is to store it in water-filled spent-fuel bays. There, the water provides cooling as well as shielding against the radioactivity.

Dry Storage

After several years in the spent-fuel bay (typically 6 years for CANDU natural-uranium fuel bundles), the fuel has cooled sufficiently that it can be moved out. It can then be stored in air in dry-storage modules above ground. The modules are constructed of concrete, which provides the necessary shielding, while air provides the cooling. The above-ground modules can provide dry storage for decades - even 50 years, until a permanent disposal facility is available.

Permanent Disposal

The ultimate step is the permanent disposal of either the irradiated fuel as is, or of the wastes arising from reprocessing. The aim is to permanently and safely dispose of the radioactive material so that it is isolated from the biosphere for an appropriate length of time - say, 10,000 years. The method which is under consideration in many countries is geologic disposal. This will be described in a separate lecture.

Conclusion

In an era of expanding world population, a strong desire in the developing countries for a standard of living equal to that already enjoyed in the developed world, pollution and concern for the environment, the threat of global warming, what is most important to you? What will be most important to future generations? A reliable energy source? Or conservation, a much lower level of energy consumption to cut down on pollution? The price of energy? Fuels which “guarantee” non-proliferation of sensitive material? Or the extension of precious natural resources?

Energy has become an important component of our way of life. More and more in the future, societies will have to face choices on how much to use, and where to get it.