Science of Nuclear Energy and Radiation

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1998 June

The Nuclear Fuel Cycle

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Topic of Discussion

Nuclear fuel cycle. Will cover various phases in use of nuclear fuel, from mining to disposal, and look at different forms that nuclear fuel can take in a reactor. Specific emphasis on possible applications to CANDU reactors.

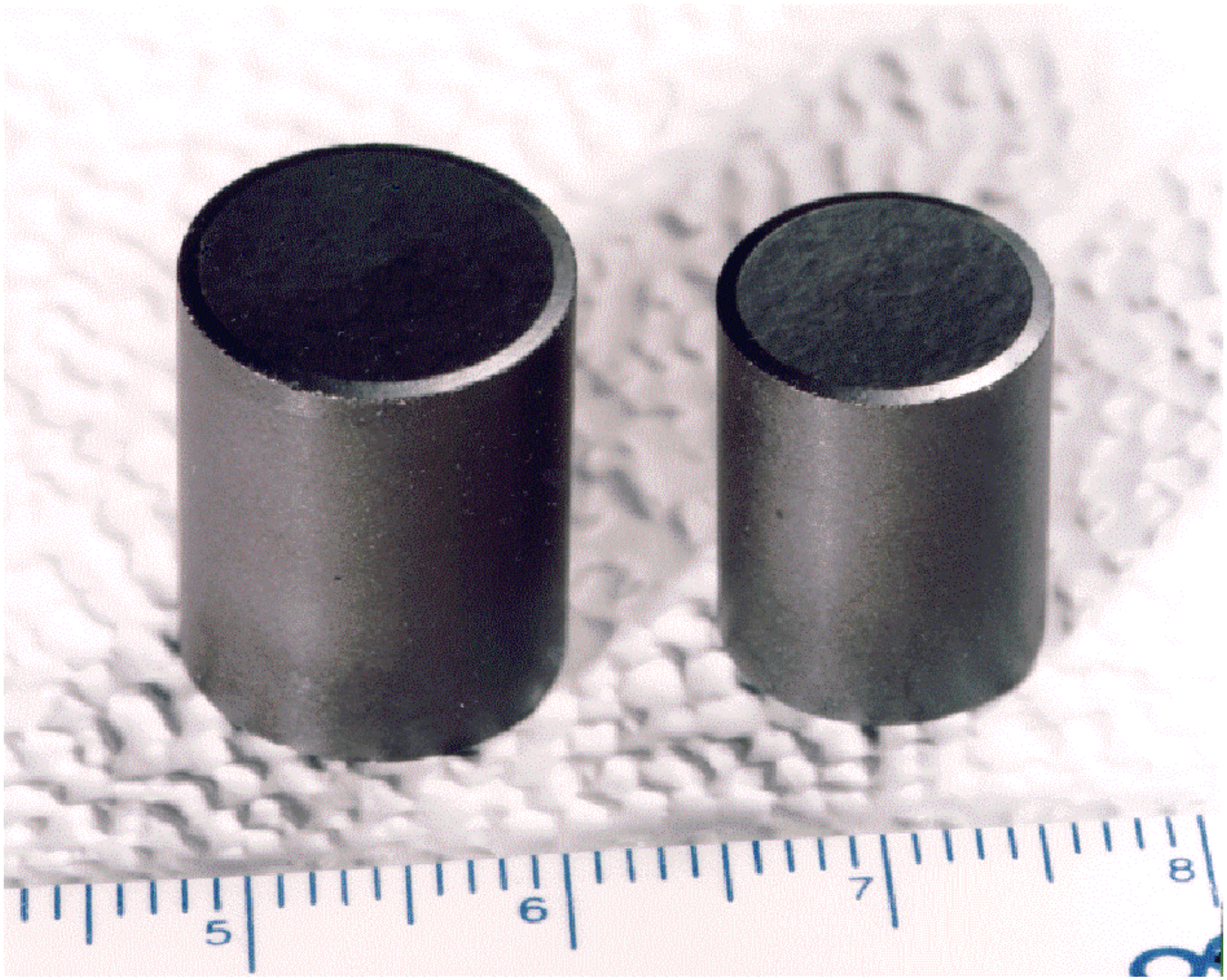
Opportunities to ponder issues with important social impact: use of resources, efficiency and economy of utilization, “throw away or recycle”, possible proliferation of prescribed materials, and how to deal with fuel after it’s irradiated.

Front End: Mine to Fuel

Front end: production of nuclear fuel. First phase obviously mining of uranium. Canada (Sask.) has large deposits of uranium ore, biggest uranium producer in world: ~ 30% of world uranium market.

- uranium leached out of uraninite, gives yellowcake, U_3O_8
- U_3O_8 reduced with H to UO_2 powder, compacted into pellets, sintered to a hard ceramic, ground to 12-mm diameter, 16-mm length

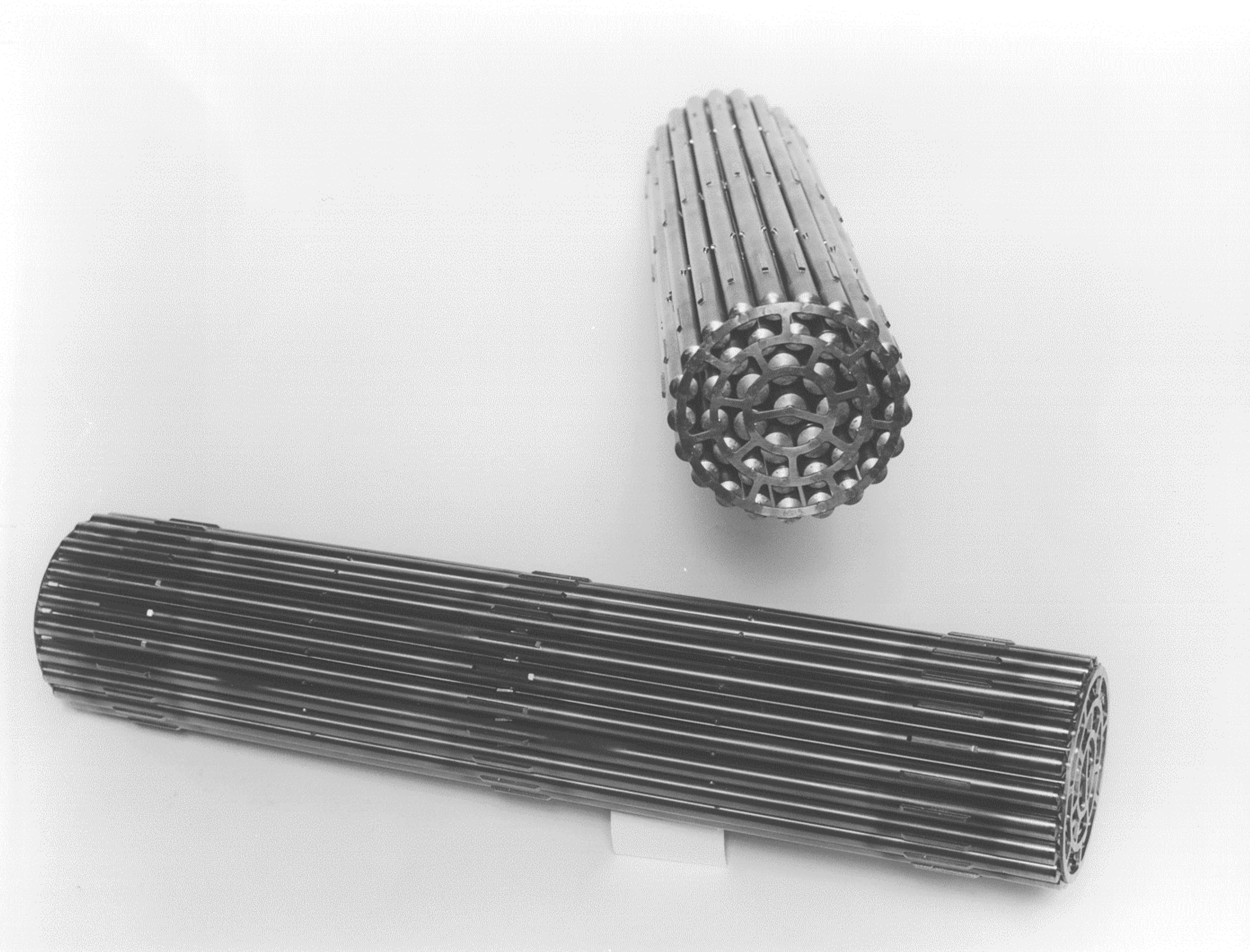
Pellets

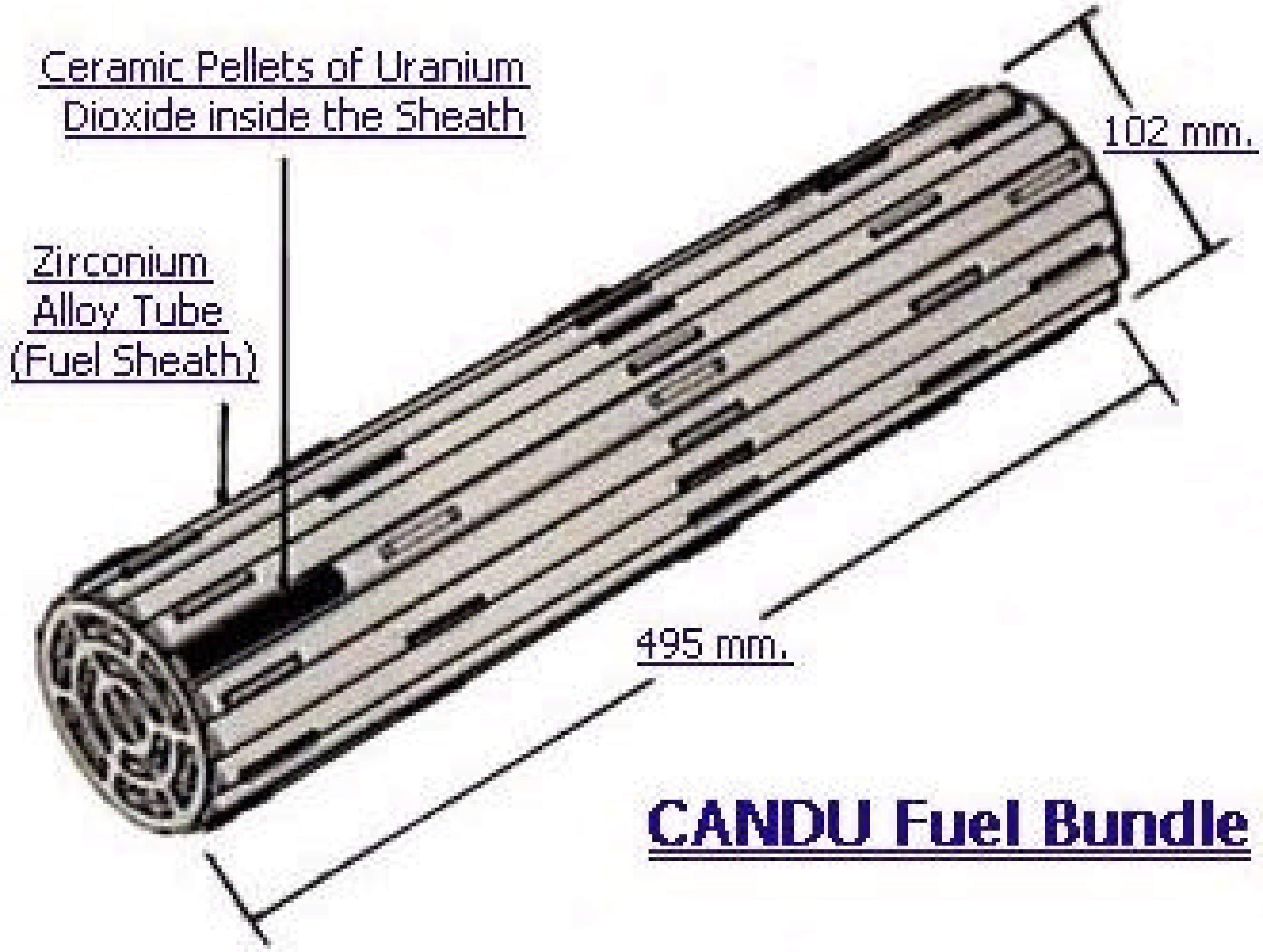


From Mine to Fuel (Cont'd)

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.




Ceramic Pellets of Uranium Dioxide inside the Sheath
Zirconium Alloy Tube (Fuel Sheath)
102 mm.
495 mm.
CANDU Fuel Bundle

Fuel Enrichment

Above sequence applies to natural-uranium fuel, as used in CANDU reactors.

For other reactors, uranium must be enriched in ^{235}U. In this case yellowcake is first converted to gaseous uranium hexafluoride, UF_6, then subjected to enrichment (by gaseous diffusion or centrifuge process).

Enrichment increases manufacturing cost of nuclear fuel significantly.

Once-Through Fuel Cycle

Only new fuel enters reactor, and once used up, is removed permanently for storage and eventual disposal.

Main energy source in uranium fuel is initially fission in ^{235}U. However, plutonium is produced from neutron absorption in "fertile" ^{238}U. ^{239}Pu, ^{241}Pu both fissile, contribute to energy released: plutonium is both created and burned *in-situ*. In CANDU, half total energy originates in Pu fissions.

Once-Through Fuel Cycle (Cont'd)

As fuel is burned in CANDU, the ^{235}U is depleted, but there is a net increase of plutonium with time.

Fissile component starts at 0.71% (^{235}U concentration in natural uranium). At discharge, total fissile component still 0.50% (0.23% ^{235}U, 0.27% fissile Pu): much energy left in irradiated fuel. Discharged not because fully used-up, but neutron-absorbing fission products have built up, become a net load on system.

Once-Through Fuel Cycle (Cont'd)

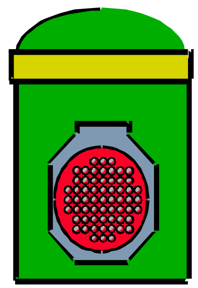
Typical light-water fuel, initial fissile content is 3.5% ^{235}U, at discharge ~1.5% (0.9% ^{235}U, 0.6% fissile Pu): > twice fissile content of natural uranium!

The once-through cycle is simple, but "spent" fuel really far from spent! Simply "throwing away" energy in discharged fuel is in fact extremely wasteful.

CANDU and PWR Fuel

Natural Uranium

0.7% U-235



CANDU

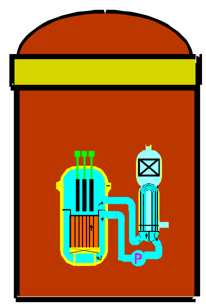
Spent NU CANDU Fuel

0.23% U-235

0.27% Pu_f

Enriched Uranium

3.5% U-235



PWR

Spent PWR Fuel

0.9% U-235

0.6% Pu_f

Once-Through Fuel Cycle (Cont'd)

Once-through nuclear fuel cycle not compatible with "reduce, reuse, recycle" philosophy. Two reasons why once-through cycle continues to be used:

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

Alternative Fuel Cycles for CANDU

Neutron economy of CANDU permits natural uranium + gives great flexibility for application of other fuels. Some alternatives described here. Idea is to extend resources by increasing uranium utilization, i.e., energy per kg mined U.

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

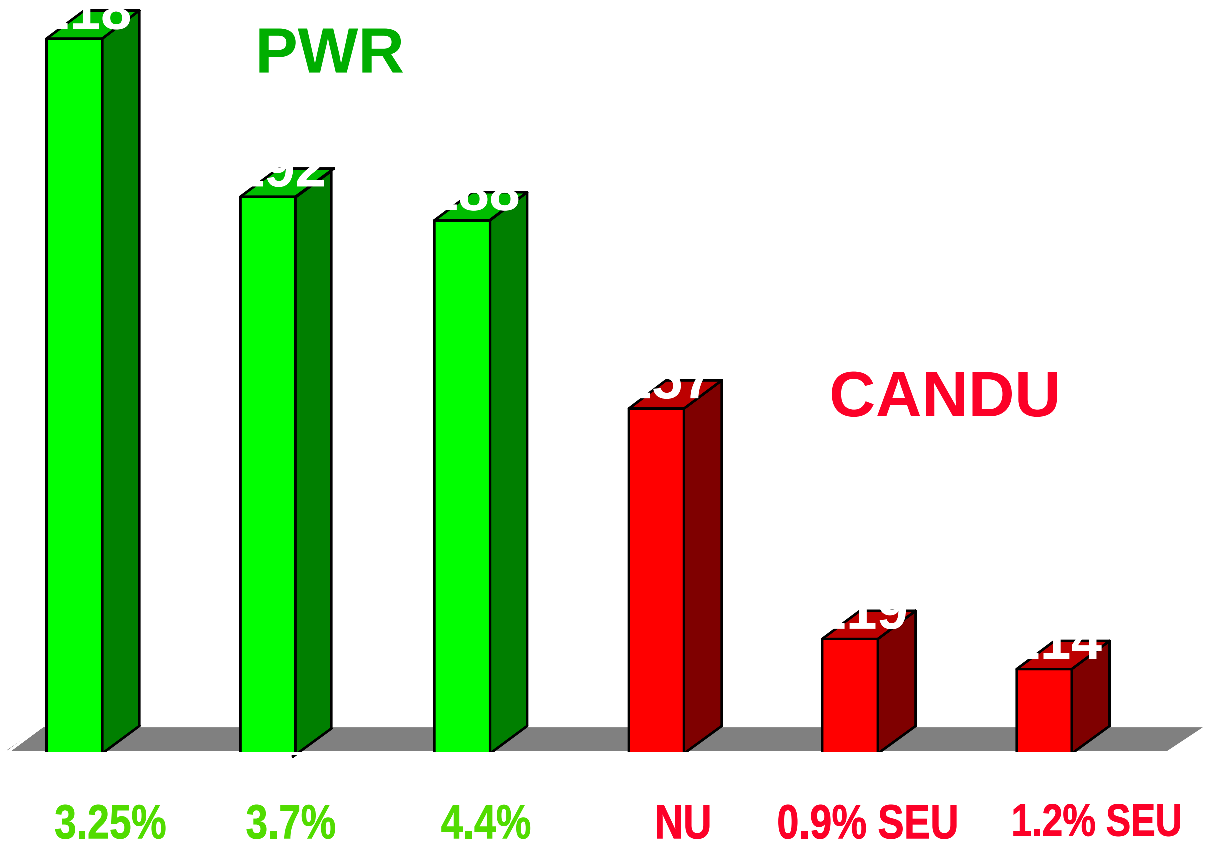
Slightly Enriched Uranium

Slightly enriched uranium (SEU) contains greater concentration of ^{235}U than natural uranium.

Concentrations in range 0.9-1.2% (cf 0.71% in natural U) can be used in CANDU without changes in reactor, and with optimum uranium utilization.

Light-water reactors (LWR) use enriched U, but because of poorer neutron economy, need enrichments of ~ 3% and greater.

Uranium Utilization



Recovered Uranium

Fuel discharged from LWR contains ~0.9% ^{235}U. If fuel reprocessed so that Pu and U are separated, then **recovered uranium** ~ equivalent to SEU, could be used in CANDU.

Recovered uranium available from commercial fuel reprocessors, but not usable as is in other reactors - enrichment too low: Use in CANDU would in effect reduce amount of fuel waste from other reactors: **synergism** between CANDU and other reactors.

Mixed-Oxide Fuel (MOX)

If fuel is reprocessed, then fissile Pu also available: in $\mathbf{PuO_2}$ form, could be mixed with "virgin" $\mathbf{UO_2}$ to make mixed-oxide (MOX) fuel to be burned in CANDU.

With sufficient enrichment, MOX can also be used in LWR - **already** used in Europe, but limited to ~1/3 core. U.S. does not burn MOX.

Fuel cycle aims at > total energy from original mined U, + amount of waste per unit of electricity produced much reduced.

Weapons-Derived Pu

MOX can also be made starting with Pu derived from weapons. U.S., Russia have agreed to reduce nuclear arsenals, >100 tonnes of Pu from weapons.

This use of military Pu reactors is 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) reprocessing separates U, Pu - considered by some as proliferation risk.

DUPIC: Direct Use of PWR Fuel in CANDU. Research Canada-Korea project - alternative to chemical reprocessing.

"Spent" PWR fuel first mechanically decladded, then treated by **dry** oxidation-reduction process to remove volatile fission products. Yields powder which can be pressed into pellets again.

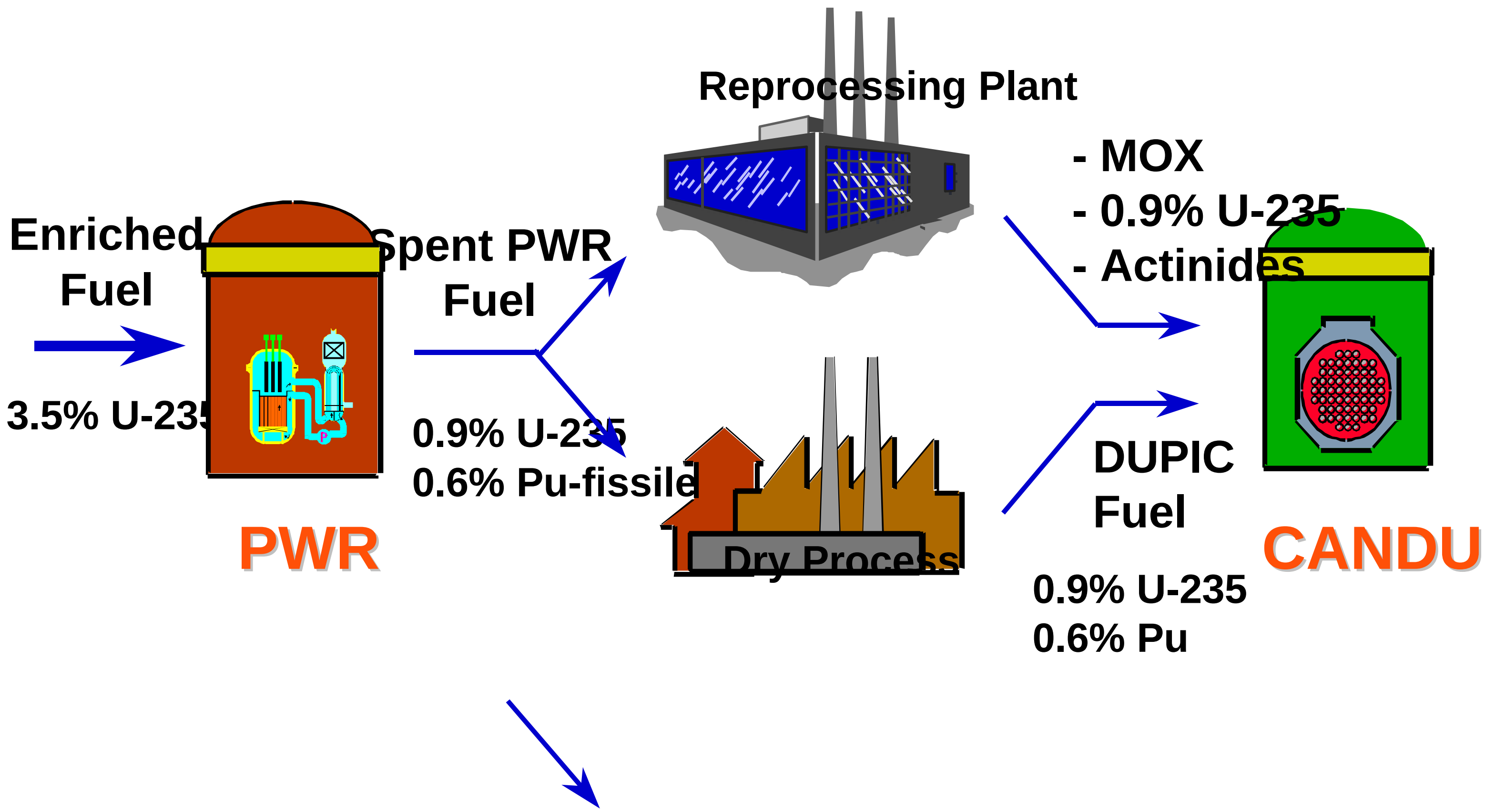
DUPIC (Cont'd)

DUPIC does not involve chemical separation of U, Pu - superior safeguardability. Fuel will have a fissile content of ~ 1.5%, so cannot be used in PWRs.

But in CANDU, would yield ~ **twice as much** energy again asproduced in original PWR cycle - ideal **synergism** between CANDU and PWR: Again, total waste much reduced.

Research now: some DUPIC fuel elements have been produced, test irradiations to be conducted.

CANDU / PWR Synergism



"Unconventional" reprocessing . . .
"Advanced" recycling . . .

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 probability of fission is much smaller at high neutron energies, number of neutrons produced per fission is higher, and extra neutrons can be used to produce more Pu from fertile ^{238}U. In fact, **more fissile material can be produced than is consumed!** Fast breeder reactor (FBR) creates its own fuel, potential of extending utilization of U resources to **centuries**.

Thorium Cycle

There is another fertile isotope besides ^{238}U: ^{232}Th, 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 precious uranium resources.

Back End - Bays

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

Spent-Fuel Bays

Fuel which comes out of reactor is “hot” - both temperature-hot and radioactivity-hot. First step in dealing with fuel is storage in water-filled spent-fuel bays. There, water provides cooling, and shielding against the radioactivity.

Back End - Air Storage

After several years in spent-fuel bay (typically 6 years for CANDU natural-U fuel), fuel has cooled sufficiently to be moved out.

Can then be stored in air in dry-storage modules above ground. Modules constructed of concrete, which provides shielding, while air provides cooling. Can provide dry storage for decades - even 50 years, until a permanent disposal facility is available.

MACSTOR at Gentilly 2

Back End - Permanent Disposal

Ultimate step is permanent disposal of either the irradiated fuel as is, or of wastes arising from reprocessing.

Aim is to permanently and safely dispose of radioactive material so it is isolated from biosphere for an appropriate length of time - say, 10,000 years.

Method under consideration in many countries is geologic disposal - described in a separate lecture.

Conclusion

Expanding world population, strong desire in developing countries for standard of living equal to the West's, pollution and concern for the environment, threat of global warming, what is most important to you? To future generations?

A reliable energy source? Or conservation, to cut down on pollution? Price of energy? Fuels which "guarantee" non-proliferation of sensitive material? Or extension of precious natural resources?

Conclusion (Cont'd)

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.