Nuclear Fuel Cycle: UPSC Notes for Science and Technology

The nuclear fuel cycle (chain) is a series of different stages that a nuclear fuel progresses through from its creation to its safe disposal. It includes front end steps (preparing the fuel), service period steps (usage of the fuel during the reactor process) and the back end steps (steps needed to safely dispose of or reprocess the fuel).

Nuclear Fuel Cycle is an important topic in the Science and Technology section of the UPSC Exams.

Basic Concept of Nuclear Fuel Cycle

Fissionable material that can sustain a chain reaction with neutrons is what nuclear power relies on. Uranium and Plutonium are examples of such materials. In order to increase the chances of a fission event to happen, some, if not most, nuclear reactors will use a moderator to lower the kinetic energy of the neutrons . This allows reactors to use material with far lower concentration of fissile isotopes than are needed for nuclear weapons. Materials such as graphite and heavy water are the most commonly known effective moderator materials, because they slow the neutrons through collisions without absorbing them. Reactors using heavy water or graphite as the moderator can operate using natural uranium.

Natural water is used in a light water reactor (LWR). It requires fuel enriched to higher concentrations of fissile isotopes. Typically, LWRs use uranium enriched to 3–5% U-235, the only fissile isotope that is found in significant quantities in nature. One alternative to this low-enriched uranium (LEU) fuel is mixed oxide (MOX) fuel produced by blending plutonium with natural or depleted uranium, and these fuels provide an avenue to utilize surplus weapons-grade plutonium. Another type of MOX fuel involves mixing LEU with thorium, which generates the fissile isotope U-233.

Some reactors do not use moderators to slow the neutrons. Like nuclear weapons, which also use unmoderated or "fast" neutrons, these fast-neutron reactors require much higher concentrations of fissile isotopes in order to sustain a chain reaction. They are also capable of breeding fissile isotopes from fertile materials; a breeder reactor is one that generates more fissile material in this way than it consumes.

Types of Nuclear Fuel Cycle

Some of the most common types of Nuclear Fuel Cycles are highlighted below:

Once-through nuclear fuel cycle

Not a nuclear fuel cycle in the true sense, fuel is used once and then sent to storage without further use save additional packaging to provide for better isolation from the biosphere. This method is favored by six countries: the United States, Canada, Sweden, Finland, Spain and South Africa. Some countries, notably Finland, Sweden and Canada, have designed repositories to permit future recovery of the material should the need arise.

Plutonium cycle

Here, the fission products, minor actinides, activation products, and reprocessed uranium are separated from the reactor-grade plutonium, which can then be fabricated into MOX fuel. There are no current plans to reuse MOX fuel-based plutonium in a thermal reactor as the proportion of the non-fissile even-mass isotopes of plutonium rises with each pass through the cycle.

Minor actinides recycling

There are proposals minor actinides could be used in a power reactor that needs immediate attention along with using plutonium.Tests are already being conducted in which americium is being used as a fuel.

In principle, it should be possible to derive energy from the fission of any actinide nucleus. With a careful reactor design, all the actinides in the fuel can be consumed, leaving only lighter elements with short half-lives. Whereas this has been done in prototype plants, no such reactor has ever been operated on a large scale.

Thorium Cycle

In the thorium fuel cycle thorium-232 absorbs a neutron in either a fast or thermal reactor. The thorium-233 beta decays to protactinium-233 and then to uranium-233, which in turn is used as fuel. Hence, like uranium-238, thorium-232 is a fertile material.

After starting the reactor with existing U-233 or some other fissile material such as U-235 or Pu-239, a breeding cycle similar to but more efficient than that with U-238 and plutonium can be created. The Th-232 absorbs a neutron to become Th-233 which quickly decays to protactinium-233. Protactinium-233 in turn decays with a half-life of 27 days to U-233. In some molten salt reactor designs, the Pa-233 is extracted and protected from neutrons (which could transform it to Pa-234 and then to U-234), until it has decayed to U-233. This is done in order to improve the breeding ratio which is low compared to fast reactors.

Thorium is at least 4-5 times more abundant in nature than all of uranium isotopes combined; thorium is fairly evenly spread around Earth with a lot of countries having huge supplies of it; preparation of thorium fuel does not require difficult and expensive enrichment processes; the thorium fuel cycle creates mainly Uranium-233 contaminated with Uranium-232 which makes it harder to use in a normal, pre-assembled nuclear weapon