Chapter

Introductory Chapter: From the Cradle to the Grave for the Nuclear Fuel Cycle

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1. Introduction

This chapter will focuses on the brief topics of Nuclear Fuel Cycle. It will provide advanced level for understanding of the complete fuel cycle by following nuclear fuel from its origin and fabrication, through its stay in the reactor with all alterations induced there, and ending with reprocessing options and waste management issues for the spent nuclear fuel. In other words: "Nuclear fuel – from cradle to grave". Moreover, it covers radiation protection issues throughout the nuclear fuel cycle.

2. Front end of the fuel cycle which includes the following items

2.1 Uranium exploration and mining

Uranium mining is the process by which uranium metal is extracted from the earth. In 2019, the worldwide generation of uranium produced 53,656 tons. The top three producers were Kazakhstan, Canada and Australia, which together account for 68 percent of the world's uranium generation. Namibia, Niger, Russia, Uzbekistan and China were other vital uranium-producing nations in excess of 1,000 tons per year [1]. Mining uranium is almost exclusively used as fuel for nuclear power plants. Uranium is extracted by in-situ filtration (57% of the world's generation) or by ordinary underground or open-pit metal mining (43% of the generation). A filtering arrangement is pumped down in the in-situ mining, penetrating holes into the uranium metal store where the mineral minerals are broken up.

At that point, the uranium rich liquid is pumped back to the surface and prepared to extract the uranium compounds from the structure in regular mining, metals are treated by pounding the metal materials to a uniform molecule measure and after that treating the mineral to extricate the uranium by chemical leaching [2]. The processing handle usually produces dry powder-form fabric composed of common uranium, "yellowcake," which is marketed as U3O8 on the uranium display.

2.2 Uranium enrichment

The nuclear fuel used in a nuclear reactor needs to have a higher U235 isotope concentration than that found in natural uranium ore. In light water reactors (the most common reactor design in the USA), U235 is fissionable when concentrated (or 'enriched'). The nucleus of the atom breaks apart during fission, creating both heat and extra neutrons.

These extra neutrons can cause additional, nearby atoms to fission under controlled conditions and a nuclear reaction can be maintained. Via a controlled nuclear reaction inside the nuclear reactor, the heat energy released can be harnessed to generate electricity. The U235 isotope is commercially enriched to 3 to 5 percent (from the natural state of 0.7 percent) and then further processed for nuclear fuel output.

Uranium oxide is converted to the chemical form of uranium hexafluoride (UF6) at the conversion plant to be used in an enrichment facility. UF6 is used for a few reasons; 1) the fluorine portion has only one isotope that occurs naturally, which is an advantage during the enrichment processing the fluorine does not contribute to the weight difference when separating U235 from U238), and 2) UF6 exists as a gas at an optimal operating temperature. There are several enrichment processes utilized worldwide. They are:

- Gaseous Diffusion
- Gas Centrifuge
- Laser Separation

The first industrial method used to enrich uranium in the United States was gaseous diffusion. These facilities used large quantities of energy and the existing gaseous diffusion plants became outdated as the centrifuge technology matured. All of them have been replaced worldwide by second-generation technology, which needs much less energy to generate comparable quantities of separated uranium. Uranium hexafluoride (UF6) gas was injected into the pipes of the plant at a gaseous diffusion enrichment plant, where it was pumped through special filters called barriers or porous membranes.

The holes in the barriers were so small that the UF6 gas molecules barely had enough space to move through. The isotope enrichment occurred because the lighter molecules of UF6 gas (with atoms U234 and U235) spread faster through the barriers than the heavier molecules of UF6 gas containing U238.

However one barrier wasn't enough. Until UF6 gas contained enough U235 to be used in nuclear fuel, several hundreds of barriers were required, one after the other. The enriched UF6 gas was separated from the pipes at the end of the operation and condensed back into a liquid that was then poured into containers. Before it was transported to fuel fabrication facilities, the UF6 was allowed to cool and solidify. The current method by which commercial enrichment is conducted in the United States is gas centrifuge enrichment. UF6 gas is positioned and rotated at a high velocity in a gas centrifuge cylinder. A strong centrifugal force is generated by this rotation so that the heavier gas molecules (UF6 containing U238 atoms) travel towards the outside of the cylinder. Closer to the middle, the lighter gas molecules (containing U235) gather. The slightly enriched stream in U235 is extracted and fed into the next centrifuge; the next higher level. The slightly depleted stream is recycled back into the next lower stage (with a lower concentration of U235).

Long lines of several revolving cylinders are contained in a gas centrifuge factory. In both series and parallel formations, those cylinders are related. To shape trains and cascades, centrifuge machines are interconnected. The UF6 is enriched to the required amount at the final withdrawal stage.

For potential use to enrich uranium, the laser separation technology is under development. By extracting isotopes of uranium with lasers, uranium can be enriched. Laser light can excite molecules; this is called photoexcitation. Lasers will raise the energy in the electrons of a particular isotope, alter its properties and allow it to be separated. Three main systems, which are laser systems, optical systems, and the separation module system, are used in the enrichment process. In order to deliver highly monochromatic light, tunable lasers can be produced. A particular isotopic species may be photo-ionized by the light from these lasers while not affecting other isotopic species. Chemically, the infected species is then modified, which allows the substance to be isolated. The laser separation technology developed by DOE uses as its feed material a uranium metal alloy, while UF6 is used as the feed material in the Separation of Isotopes by Laser Excitation process.

2.3 Fuel fabrication

Fuel production installations turn enriched uranium into nuclear reactor fuel. Mixed oxide (MOX) fuel, which is a mixture of uranium and plutonium, may also be used in fabrication. Usually, the manufacture of fuel for light water reactors (LWR) (regular commercial power reactors) begins with the receipt of low-enriched uranium from an enrichment facility, in the chemical form of uranium hexafluoride (UF6).UF6 is heated to a gaseous state in solid form in tubes, and then the UF6 gas is chemically treated to form a powder of uranium dioxide (UO2). This powder is then pressed into pellets, loaded into Zircaloy tubes, sintered into ceramic form, and constructed into fuel assemblies. If it is a boiling-water reactor or a pressurized-water reactor depends on the type of light water reactor.

MOX fuel differs from low-enriched uranium fuel in that the powder used to form fuel pellets is comprised of both uranium dioxide (UO2) and plutonium dioxide (PuO2). The MOX fuel will be used in light-water reactors.

Small reactors that do not produce electrical power but are used for research, testing and training are non-power reactors. Analysis reactors and reactors used to manufacture irradiated target materials may be included in non-power reactors. The configuration of the fuel varies with the kind and manufacturer of the reactor. The plate-type fuel consists of several thin sheets containing an aluminum-clad uranium mixture. Another fuel is in the form of rods and is made up of a combination of uranium and zirconium/hydride.

3. Nuclear fuel in reactor

Nuclear fuel is the fuel which is used to support a nuclear chain reaction in a nuclear reactor. These fuels are fissile, and the radioactive metals uranium-235 and plutonium-239 are the most common nuclear fuels. A cycle known as the nuclear fuel cycle is made up of all the steps involved in collecting, refining, and using this fuel. Many nuclear fuels produce heavy elements of fissile actinide that are able to undergo and sustain nuclear fission. Uranium-233, uranium-235 and plutonium-239 are the three most applicable fissile isotopes. As a slow-moving neutron strikes the unstable nuclei of these atoms, they split, forming two daughter nuclei and two or three more neutrons. Then these neutrons go on to split more nuclei. This produces a self-sustaining chain reaction that is regulated or uncontrolled by a nuclear bomb in a nuclear reactor.

4. Back end of the fuel cycle

For a period of five years or so, the fuel is first placed in a storage pool, the time to let the most active fission products decrease or vanish. After those five years, a decision as to whether or not to reprocess is made. If not, so as it is the fuel must be stockpiled.

Research is currently underway on the feasibility of the final disposal of spent fuel deep underground; decisions on such disposals are yet to be made. Meanwhile the waste accumulated above ground is accumulating around the power plants. If a reprocessing decision is taken, the spent fuel is transported to a reprocessing plant where it is deposited in a nearby pool for a few more years. Reprocessing requires separating what can be recycled from what can be labeled as actual waste - uranium and plutonium. Usually, 95% of the fuel consists of plutonium, which also contains about 1% of the fissile isotope 235, more than natural uranium. The spent fuel also contains an additional 1% of plutonium, of which 70% of the isotopes are fissile and can generate electricity. It is possible to re-enrich this uranium and recycle the plutonium to join the fresh fuel composition to power other reactors.

Fission products and small actinides make up the remaining 4 percent of the spent fuel. They account for about 98% of their gamma and beta radioactivity. These are the real products of waste. This waste is highly radioactive, but it is conditioned by embedding it in glasses or ceramics that provide fewer long- term environmental risks than the disposal without reprocessing of spent fuel 'in-state.' The final disposition of these vitrified waste is yet to be determined, but their stockpiling in interim storage facilities is less of a concern as their mass is much smaller than the spent fuel.

Over a number of years, the IAEA has developed a comprehensive set of safety series documentation, which addresses, in a structured manner, many of the various nuclear fuel cycle safety needs identified by Member States. Since 1996 the IAEA Safety Standards series of documents has been subject to a process of planned change from its original structure of Safety Fundamentals, Safety Standards, Safety Guides and Safety Practices, to a new structure with a single Safety Fundamentals document supported by Safety Requirements and Safety Guides. The existing IAEA documents cover the safety of nuclear installations (predominantly, but not exclusively, nuclear power plants), radioactive waste management, radiation protection and transport safety [3].

5. Nuclear Power Station at production of energy

In the 1950s, the first commercial nuclear power plants began operation. Out of about 440 power plants, nuclear energy now generates about 10 percent of the world's electricity. Nuclear power is the world's second largest low-carbon power source (29 percent of the total in 2017). One of condition to be as source of renewable energy. Over 50 countries utilize nuclear energy in about 220 research reactors. In addition to research, these reactors are used for the production of medical and industrial isotopes, as well as for training. In 2018, 12 countries generated at least one quarter of their electricity from nuclear power. About three-quarters of France's energy comes from nuclear power, more than half from Hungary, Slovakia and Ukraine, and one-third or more from Belgium, Sweden, Slovenia, Bulgaria, Switzerland, Finland and the Czech Republic.

Normally, South Korea gets more than 30 percent of its electricity from nuclear power, while about one-fifth of its electricity comes from nuclear power in the USA, UK, Spain, Romania and Russia. For more than one-quarter of its energy, Japan is used to rely on nuclear power and is expected to return to somewhere near that amount.

With a total net capacity of 1.6 GWe, Mexico has two operable nuclear reactors. In 2019, 4.5% of the country's electricity was generated from nuclear power. With a total net capacity of 13.6 GWe, Canada has 19 operable nuclear reactors. In 2019, 15 percent of the electricity generated by nuclear power in the world.

With a total net capacity of 96.8 GWe, the USA has 95 operable nuclear reactors. Nuclear power provided 20% of the nation's electricity in 2019. With a total net capacity of 1.6 GWe, Argentina has three reactors. In 2019, the nation produced 6% of its nuclear power. There are two reactors in Brazil, with a combined 1.9 GWe net capacity.

In 2019, 3% of the nation's electricity was generated by nuclear power. There are seven operable nuclear reactors in Belgium, with a total net capacity of 5.9 GWe. In 2019, 48% of the electricity generated by nuclear power in the world.

With a total net capacity of 2.8 GWe, Finland has four operable nuclear reactors. Nuclear power provided 35% of the country's electricity in 2019. A fifth-1720 MWe reactor. France has 56 nuclear reactors which are operational, with a total net capacity of 61,4 GWe. Nuclear power provided 71% of the country's electricity in 2019. Germany, with a total net capacity of 8,0 GWe, continues to run six nuclear power reactors.

In 2019, 12.5% of the electricity in the country was produced by nuclear power. With a total net capacity of 45.5 GWe, China has 47 operable nuclear reactors. Nuclear power provided 5% of the country's electricity in 2019. India has 22 nuclear reactors which are operational, with a total net capacity of 6.2 GWe. In 2019, 3% of the nation's electricity was generated by nuclear power.

Japan has 33 nuclear reactors that are operational, with a total net capacity of 31,7 GWe. Just nine reactors were brought back online at the start of 2020, with a further 17 in the process of restarting the approval process following the Fukushima accident in 2011. In the past, 33% of the country's electricity came from nuclear power; in 2019, the figure was just 8% [4].

6. Is a nuclear energy renewable or nonrenewable source?

There are three main types of fossil fuels consider as nonrenewable energy sources: Coal, Oil and Natural Gas. They are nonrenewable energy sources because they exist in finite quantities. On the other hand, renewable energy means that they can naturally replenish themselves over time. Six main sources of renewable energy: Rain, Wind, Sunlight, Tides, Waves and Geothermal heat.

The researches with the nuclear energy as renewable energy source due to the following items:

Low-Carbon Emission: This is the main argument for nuclear energy being renewable. Nuclear power plants do not pollute the air or emit greenhouse gases [5].

It Is Replenishable: It takes more time than with the other sources, but in the end, they will appear again.

Fissile Material: Uranium supplies existing now can supply nuclear power only for approximately 1000 years.

While the against for the nuclear energy is consider the renewable source, due to:

Finite Uranium Deposit: Uranium deposit found on Earth is finite. Thus this resources one day will disappear, in addition to the following items:

- Nuclear power reactors give away harmful nuclear waste.
- Radioactive waste can be extremely toxic, causing burns and increasing the risk for cancers, blood diseases
- Storage of nuclear waste is very expensive.

Example the nuclear disasters that took place over the Chernobyl, Fukushima.

So, is nuclear energy renewable? There is no clear answer for that now. There are pertinent arguments on both sides of the debate [6, 7].

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