Nuclear Power Generation: Spent Fuel Management

Siro Genolet

Electromechanical Engineering Department, Universidad Tecnológica Nacional, Facultad Regional Paraná
1033 Almafuerte Av. Paraná, Argentina

sirogenolet@alu.frp.utn.edu.ar

***Abstract*— Over the years, spent fuel and radioactive waste have been accumulating in nuclear power plants and storage facilities all around the world. This poses a risk for both people and the environment, since this waste is extremely dangerous. In this paper, the management of spent fuel from nuclear power plants is approached with the aim of shedding light into ways this material can be managed in a safe way. In order to achieve that, the paper is organized in two main parts. In the first one, a brief description of some basic aspects of nuclear reactors is provided, emphasising in nuclear fuels. In the second part, a description of current methods to manage spent fuel is developed. At the end of the second part, a summary of the strategies used by different countries to manage spent fuel is presented. It is expected that this paper might help raise awareness of what this topic represents in terms of safety, and what countries are doing to approach it.**

***Resumen*— A lo largo de los años, el combustible nuclear gastado y los residuos radioactivos han ido acumulándose en las plantas nucleares y en los sitios de almacenamiento alrededor de todo el mundo. Esto representa un riesgo tanto para las personas como para el medio ambiente, ya que estos residuos son extremadamente peligrosos. En este trabajo, el manejo del combustible gastado proveniente de plantas nucleares es abordado con el objetivo de dar a conocer algunas maneras en las que estos materiales pueden ser tratados de una forma segura. A tal fin, el trabajo ha sido organizado en dos partes principales. En la primera, se proporciona una breve descripción de algunos aspectos básicos sobre reactores nucleares, haciendo énfasis en los combustibles nucleares. En la segunda parte, se desarrolla una descripción de los métodos utilizados actualmente para el manejo del combustible gastado. Al final de la segunda parte, se presenta un resumen de las estrategias de algunos países para el manejo del combustible gastado. Se espera que este trabajo ayude a concientizar sobre lo que este tema representa en términos de seguridad, y dar a conocer los esfuerzos de algunos países para abordarlo.**

I. Introduction

Daily, the consumption of electrical energy increases around the world. In order to produce that rising amount of energy to meet the demand, countries need to build large power plants to satisfy the needs of both people and industries.

Although the energy is needed, it should be produced in a clean, sustainable, and modern way as the United Nations states in its Sustainable Development Goals (SDGs), especially in their SDG Nº 7 “Ensure access to affordable, reliable, sustainable and modern energy for all” [1]. To achieve that, improving the current power production infrastructure and their resource management is mandatory.

Renewable energies are highly positive in terms of not polluting the environment. However, as they rely on weather conditions, they are not able to produce energy at any given time. A reliable technology, capable of producing energy at any given time is needed. This kind of infrastructure is called base load plant.

Base load power infrastructure relies mainly on hydroelectric power, fossil fuels, such as carbon, gas and different oils, and nuclear power. The first two are the ones that have the greatest impact on the environment: hydroelectric for its impact on the rivers and flooded areas, and thermal plants for their greenhouse gases emission.

Despite the fact that nuclear power generation does not produce greenhouse gases, it produces highly radioactive materials at the end of the fuel cycle. In this sense, it is important to manage these materials in an effective, affordable and, more importantly, safe way for this technology to become more widely used around the world. In this paper, this topic will be approached, and the methods used by different countries to manage the spent fuel at the end of the cycle will be analyzed.

In order to achieve the objective stated above, this paper is organized in two parts. In the first part, a description of some basic aspects of nuclear reactors as well as the fuel used will be presented. In the second part, a summary of the different methods that countries use to manage spent nuclear fuel will be carried out. It is expected that this paper might help raise awareness of what this topic represents in terms of safety.

II. Nuclear Fuel Cycle

To be able to understand the nuclear fuel cycle, it is important to know how a nuclear reactor works. In the next paragraphs, a brief description of what a nuclear reactor is and some basic aspects about nuclear reactions and fuel will be developed.

A. Fission Reaction

Nuclear fission is a process by which an unstable atomic nucleus splits into two lighter nuclei and emits subatomic particles to become more stable. This process generates a great amount of energy when it is repeated in a chain reaction [3].

There are heavy nuclei, such as uranium-235 or plutonium-239, that are capable of undergoing fission when they absorb a neutron. The elements capable of doing that are called fissile elements [3]. In [Fig. 1, 4] the process by which a uranium-235 nucleus absorbs a neutron and undergoes fission is shown.

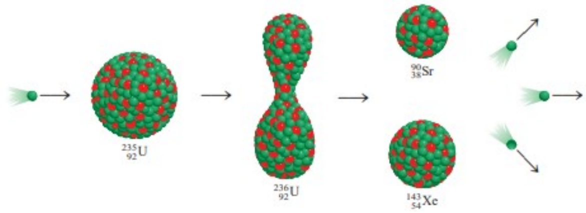

Fig. 1 Uranium-235 fission process [4].

B. Nuclear Reactors

A nuclear reactor is a device that is able to maintain a nuclear fission chain reaction for different purposes. Some of the purposes are radioisotopes production for medicine and industry, but the main purpose is electricity generation. These devices are important in daily life since nuclear electricity generation represented around 10% of the global production in 2019 and approximately one-third of the low carbon electricity [2].

In nuclear power plant reactors, the energy released from fission reactions, which is quickly transformed into heat, is usually used to boil water to produce the steam that rotates a turbine connected to an electricity generator [3].

In order to start and maintain the fission chain, a reactor must contain fissile elements, but these elements do not undergo fission by themselves. To achieve criticality, the state where the fission chain is self-sustained, some conditions are needed. In thermal reactors, the most widespread kind, the fuel needs a moderator capable of slowing down neutrons for them to be absorbed by fissile nuclei.

Different types of reactors are designed to accomplish different tasks. One of the most important aspects in thermal reactors is the kind of moderator they use; this will determine which fuel they could use and will be chosen according to the purpose of the reactor.

The main three types of reactors are moderated by light water, heavy water, and graphite. The most used types are the ones moderated by water, called Pressurized Light-Water Reactor (LWR), and heavy water, called Pressurized Heavy-Water Reactor (PHWR) [5]. Heavy water is 11% heavier than normal water since it contains deuterium, an isotope of hydrogen, and oxygen instead of hydrogen and oxygen.

In [Fig.2, 3] a scheme of a standard LWR is shown. The reactor is placed into a stainless-steel pressure vessel that can withstand hundreds of times the atmospheric pressure. The fuel is located in the inferior half of the vessel, called reactor core. There are also several control and safety systems that ensure the correct operation of the reactor, but these elements will not be described because they fall outside the scope of this paper.

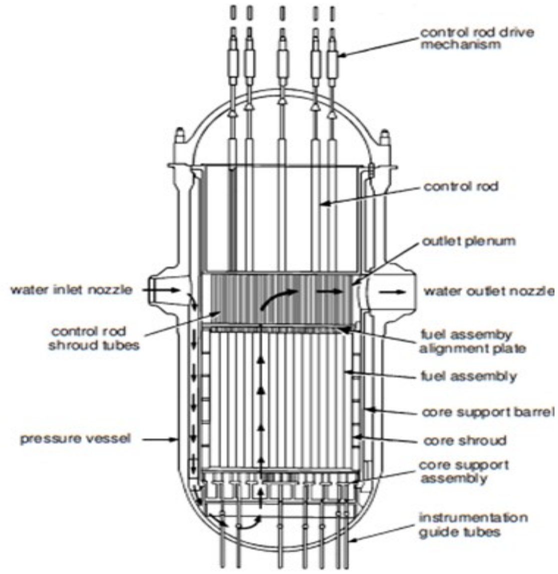

Fig. 2 Scheme of a standard LWR reactor [3].

C. Nuclear Fuels

The fuel of a nuclear reactor consists of thousands of little pellets of fissile material, usually uranium oxides or a mix of uranium and plutonium oxides. These pellets are placed into metallic tubes, which are called fuel rods and are arranged into fuel assemblies of several rods. The core of a nuclear reactor consists in several tens or even hundreds of fuel assemblies depending on the size of the reactor [5]. In [Fig.3, 5] a fuel pellet is shown, while in [Fig.4, 5] a fuel assembly is being manufactured.

Fig. 3 Uranium dioxide pellet [5]

Fig. 4 LWR Fuel Assembly [5]

In PHWR the pellets are usually made of natural uranium dioxide, and the amount of the U-235 isotope is about 0,7%. This is because the moderator allows the fission to happen even with natural uranium [3].

In other types of reactors, the uranium goes through a process of enrichment by which the amount of U-235 is usually increased to around 3% to 5%. This occurs since other moderators, like light water, do not allow the fission to happen with small concentrations of U-235. This type of fuel lasts between three and four years [3].

There are also other types of fuel that mix different uranium and plutonium oxides. Since these kinds of fuels are a subproduct of spent fuel and nuclear waste, this topic will be treated in the spent fuel management section.

D. Spent Fuel

When nuclear fuel reaches the end of its life cycle, it has already experimented some changes in its composition. A considerable part of the U-235 has turned into fission products, which means that the heavy U-235 nuclei are no longer uranium but other lighter elements because of fission. Also, a small part of the U-238 has become plutonium through a process called transmutation, by which some elements absorb neutrons and turn into a heavier element, usually called transuranic element when heavier than uranium [3]. In [Table 1, 7] the percentage of different isotopes present in spent LWR fuel is shown.

Table 1- Composition of LWR spent fuel [7].

New Fuel		Spent Fuel	
Isotope	**Percent**	**Isotope**	**Percent**
U-238	**96.7**	**U-238**	**94.3**
U-235	**3.3**	**U-235**	**0.81**
		U-236	**0.51**
		Pu-239	**0.52**
		Pu-240	**0.21**
		Pu-241	**0.10**
		Pu-242	**0.05**
		Fission Products:	**3.5**

III. Spent Fuel management in different countries

As stated in the previous section, fission products and transuranic elements are present in spent fuel. These materials, as well as U-235, are radioactive and represent a hazard to both people and the environment. A responsible, safe, and environmentally friendly way to manage them is needed.

In order to develop techniques and processes to manage nuclear waste, it is important to know the characteristics of different kinds of waste. There is no official classification of nuclear waste but the common agreement between countries is the following [3]:

- **High Level Waste (HLW)**: These are the fission products, isotopes with a short half-life which are highly radioactive. In countries where spent fuel is not reprocessed, it is treated like HLW even though it contains other kinds of waste.
- **Transuranic waste (TRU)**: These are elements heavier than uranium. These isotopes have the longest half-life, which represents a major problem, since they last thousands of years. However, they are less radioactive than HLW.
- **Low Level Waste (LLW)**: This waste does not present great concentration of actinides (transuranic mainly) and its transportation and storage do not require shielding. This waste is transported and stored in metal drums.

Each country has its own way to manage spent nuclear fuel from its power plants. There are countries that recycle a part of the fuel or reprocess it, and others that directly store the fuel without reprocessing it.

The management of spent fuel depends on several factors, such as the local laws, the financial situations and the kind of reactor or, more specifically, the kind of fuel. These processes are very complex, expensive and represent a potential hazard in every stage. That is why some countries choose not to reprocess its spent fuel.

Although there are differences between the countries´ management strategies, the first stage is the same in every nuclear power plant. This stage consists in the “cooling down” of the spent fuel. During this period, the fuel emits a great amount of energy in the form of heat, and this is because the fission products decay rapidly. For three to five years the spent fuel needs to cool down in a controlled way.

After being removed from the reactor, the spent fuel is stored in the nuclear power plant until it is transported for reprocessing or final disposal. The way to store it is using a pool where the spent fuel is kept under strict control. In some cases, the new fuel also sits in the pool until it is placed into the core of the reactor. These pools are especially built to store the fuel; they have heat removal, leakage and water level control systems; and they do not need external shield for radiation since water itself is a great shield against radiation due to its high neutron absorption. These facilities are called wet storage facilities [6].

After the cooling down process, there are two paths to follow. The first one is to store all the spent fuel, using dry storage in canisters or casks. The other path is to reprocess the spent fuel to recycle and reuse the fissile isotopes left in it [3].

Dry storage consists in placing HLW in casks or canisters especially built to withstand degradation for long periods of time. Prior to placing the fission products in storage, they are mixed with pulverized glass and melted. When the mixture becomes solid, it prevents air and water from entering it, which helps the HLW to stay away from an environment rich in oxygen. This is a key aspect because oxygen accelerates degradation in materials [3] [6].

It is important to know that in countries where the spent fuel is not reprocessed, the fuel rods are kept in dry storage as HLW. However, in this situation, the fuel rods are placed in containers which are filled with molten metal, such as lead, to maintain the geometric configuration of the fuel and make it environment-resistant when it solidifies [3]

Reprocessing Spent Nuclear Fuel (SNF) allows to recycle the uranium and transuranic elements present in SNF. The recycled materials can be reused in fuels such as Mixed Oxide fuel (MOX), which is a mix of new uranium and plutonium from SNF. Reprocessing can be carried out at different levels of partitioning, recovering only uranium and plutonium from HLW or recovering also the fission products and minor actinides (actinides except uranium and plutonium) [9].

By reprocessing SNF and separating fission products, with a short half-life, from the rest of the SNF, the amount of time that the HLW needs to be stored is diminished, since fission products only need to be isolated for about one hundred years. The TRU needs to be stored for thousands of years until it decays to a safe level [3]. When SNF is not reprocessed, all of it needs to be stored for thousands of years.

The methods previously mentioned, wet and dry storage, are just interim solutions that cannot store radioactive waste for thousands of years as needed. Nevertheless, countries that reprocess their SNF can significantly reduce the amount of TRU -the waste that lasts longer- by burning it in nuclear reactors and turning them into fission products, which last for a shorter period of time [3].

From the beginning of nuclear power generation in 1954 to the end of the year 2016, approximately 390.000 t HM (tones Heavy Metal) of SNF have been discharged from nuclear reactors, while 127.000 t HM have been reprocessed, and 263.000 t HM have been stored in both dry and wet storage. About 183.000 t HM were stored in wet storage, and 80.000 t HM in dry storage facilities [14]. In [Fig. 5, 14] this information is shown.

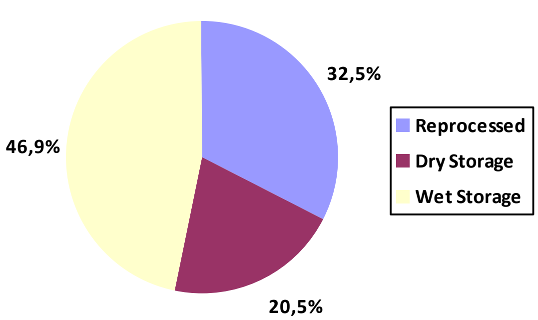

Fig. 5 Share of SNF stored or reprocessed from 1954 to 2016 [14]

The last stage in SNF management is final disposal in geological repositories, which consists in deep excavations, such as mines, where the SNF is to be disposed of. The chosen site must be dry, geologically stable, and be placed far from water resources or populated areas.

These repositories are designed to last several thousands of years without suffering damage due to water or any natural disaster. This is the reason it takes, on average, three decades to choose the location and start building this kind of facilities [8].

In some countries, nuclear power plays a key role in their energy share. Each country has adopted its own strategy to manage SNF: some of them have chosen a once-through fuel cycle without reprocessing it, and others choose to recycle the SNF in order to save uranium and, more important, reduce the amount of SNF to be stored. A brief description of the spent nuclear fuel management in some of the most important countries in terms of nuclear technology will be provided below.

A. France

The French strategy consists in reprocessing the spent fuel, extracting plutonium from the spent fuel and mixing it with new enriched uranium to produce MOX. By using this recycling scheme, France saves between 20 and 25% of natural uranium and reduces up to four times the amount of spent fuel that needs to be stored [10].

Currently, they can recycle its SNF only once and that is why this scheme is called once-through recycling. However, the French nuclear industry is aiming to be able to recycle the SNF multiple times. The main barrier to this objective is the threshold in the amount of plutonium permitted in nuclear fuel. In spite of this threshold, the engineers and scientists believe that the objective could be achieved by increasing the amount of enriched uranium present in MOX [10].

France is also trying to achieve a fully closed fuel cycle in the long term, by using Sodium-cooled Fast Reactors (SFR), which produce more fissile material than they consume. If the country achieves it, they could further reduce the amount of transuranic waste that needs to be stored, while reducing the amount of new fuel that is needed to keep the reactors working [10].

A final disposal for radioactive waste is being developed in France. The solution chosen by the French authorities is the geological disposal, which will be placed in the northeast of the country. It is expected to start receiving HLW by 2030 and to operate for one hundred years [8].

B. China

The country is developing a strategy to achieve a closed fuel cycle, by using Fast Reactors (FR), thermal reactors (LWR and PHWR), and Accelerator Driven Reactors (ADR) for recycling the spent fuel several times. The idea is to improve the current ratio in breeder reactors, which means increasing the production of fuel while reducing the amount of waste [11].

Since 2010, a new reprocessing plant has been operating to test new techniques and the stability of the process and equipment. It also produces MOX fuel for experimental fast reactors [11].

New vitrification equipment was acquired from Germany, and it is currently being tested. This equipment is used to vitrify radioactive waste for dry storage and helps in the development of several related technologies [11].

Geological disposal is being planned in China as well. The project consists in a deep geological disposal facility with its own underground laboratory for reprocessing spent fuel. It is expected to start operating by 2050 [11].

C. Russia

The Russian Federation has decades of experience in developing the nuclear industry. Alongside the United States, Russia developed a great part of the technologies today in use. This experience led to a strong nuclear program that is aiming to improve even more.

The management of spent fuel in Russia consists in reprocessing the waste to recycle and reuse it. As well as the previous strategies, this leads to a decrease in the need to store spent fuel and the need for extracting new uranium [12].

There are two facilities that reprocess the spent fuel. The first one, PA Mayak, has been operating since 1977. Here, the spent fuel is reprocessed, and the fission products are separated from the transuranic and the depleted uranium. There is also a vitrification complex, dry storage vaults, and partitioning of HLW facilities [12].

The second one is still in construction, and it consists in a centralized facility for reprocessing, storing, producing and developing nuclear fuels. It will also have an underground laboratory [12].

In the underground laboratory, studies about geological disposal will take place. Also, development of needed technologies related with final disposal of radioactive waste will be carried out [12].

Rosatom, the nuclear regulator in Russia, aims to develop a closed fuel cycle, just as China and other countries. In order to achieve this, fast reactors are used together with different types of thermal reactors. They are already testing fuels such as REMIX, a fuel made from enriched uranium, and reprocessed uranium and plutonium. Russian scientists think that REMIX fuel could be reprocessed up to seven times, in contrast with MOX, which cannot be reprocessed with current technologies. This makes Russia a step ahead of China and France in terms of SNF recycling, being the first to test this kind of fuel [12].

Although Russia is one of the world leaders in SNF recycling technology, they are a step behind in final disposal, not even having selected a place to build it. This could be due to its radioactive waste treatment plan, which includes almost every kind of HLW, and could potentially produce significantly less HLW than other countries with a similar number of nuclear power plants.

D. United States

In the United States, the SNF is not reprocessed; they rely in a once-trough fuel cycle, disposing of all of its SNF. Currently, there is no final disposal solution for SNF. A deep geological repository was being built, but the project has been stopped due to differences between the national government and the State of Nevada government, where the repository is placed, more specifically in Yucca Mountain, near the Nevada Test Site for nuclear weapons [13].

All the SNF is stored in interim storage, both wet and dry storage, across the whole country in nuclear power plants. There are also facilities to store SNF that are not placed in nuclear plants. These locations are called Away-From Reactor (AFR) facilities [14].

Currently, there is a geological disposal facility being used, called Waste Isolation Pilot Plant (WIPP), but it is exclusively for military-generated radioactive waste. The origin of this waste is the national nuclear weapons program. The plant is placed in the State of New Mexico and has been in operation since 1999 [13].

E. Argentina

The strategy of SNF management in Argentina consists in storing the spent fuel within each power plant. The SNF is placed in wet storage in several pools inside the storing facilities.

In Embalse nuclear power plant the SNF is stored in concrete silos, called Almacenamiento en Seco de Elementos Combustibles Quemados (ASECQ), after spending six years in wet storage. In Atucha I power plant, an ASEQC started its operation in late 2022. An ASEQC in Atucha II is being planned [15].

In contrast with the above-mentioned countries, Argentina has a reduced number of nuclear power plants. Therefore, the volume of SNF is considerably less than in countries like the United States or France.

The country is still evaluating whether to reprocess its SNF or to store it in geological repositories. While the decision is made, several projects to increase interim storage are being planned [15].

Spent nuclear fuel in Argentina is, by law, taken as a potential resource rather than as a waste. That is why the National Commission of Atomic Energy (CNEA) possesses the state ownership over SNF and is also responsible for its safe management [15].

IV. Conclusion

There are different approaches to the management of spent nuclear fuel around the world. Whereas some countries choose to reprocess the fuel before disposing of it, others, like the United States, choose not to reprocess the fuel to avoid possible diversion of material for nuclear weapons.

These strategies have a direct impact on the environment and people, since radioactive waste is extremely dangerous and has to be handled and discarded with caution. Well designed and implemented programs are essential to meet the safety needs and keep this technology affordable for countries.

It is important to develop strategies that allow different countries to reprocess their spent fuel. By doing that, the need for storage and final disposal is drastically reduced. Disposing of SNF without being reprocessed is not a responsible policy, since it leaves a complex issue for the future generations to solve.

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Siro Genolet is an Electromechanical Engineering student at UTN FRP: sirogenolet@alu.frp.utn.edu.ar.

The present manuscript is part of the research activities in the Inglés II lesson at Universidad Tecnológica Nacional, Facultad Regional Paraná. Students are asked to research into a topic so as to shed light on a topic of their interest within the National Academy of Engineering's Grand Challenges or the United Nations' Sustainable Development Goals frameworks. If sources have not been well paraphrased or credited, it might be due to students' developing intercultural communicative competence rather than a conscious intention to plagiarize a text. Should the reader have any questions regarding this work, please contact Graciela Yugdar Tófalo, Senior Lecturer, at gyugdar@frp.utn.edu.ar