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Processing of Nuclear Fuel Waste and Nuclear Medicine

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ABSTRACT

The analysis describes the trends in the development of nuclear energy based on the processes of processing nuclear fuel waste, technologies, equations of processes and the use of radionuclides in nuclear medicine, modern methods of nuclear medicine, as well as modern methods of nuclear fuel disposal.

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It is essential to recognize that renewable energy sources, fossil fuel-based energy sources, and nuclear energy sources each present unique and significant challenges to the environment and human health. It is natural for the public to harbor some apprehension toward nuclear energy, especially given the various accidents, explosions, and issues related to the disposal of radioactive waste that have marked its initial development.

Currently, as fossil fuel resources diminish, developed countries are striving for a harmonious development of their energy sectors. They are comparing the safety of modern advanced nuclear power plants (NPPs) with the environmental damage caused by climate change and its impact on human health. The accident at the Fukushima nuclear power plant in Japan led to restrictions on the use of nuclear energy in the country. However, after a brief period and significant changes in societal life, Japan has once again resumed the use of nuclear energy, demonstrating the irreplaceable role of NPPs in certain countries.

It is noteworthy that globally, there are plans to construct 164 reactors in the near future. This includes 40 reactors in China, 25 in Russia, 20 in India, 18 in the USA, 9 in Japan, and 8 in South Korea, with construction already started on 60 of them. The following figure illustrates the ranking of 20 countries based on the number and capacity of operational nuclear energy sources to date.

Additionally, countries such as Turkey, Poland, Vietnam, Indonesia, and others are beginning to develop their nuclear energy capabilities for the first time. All of this indicates an increasing share of nuclear energy among energy sources.

As of today, more than 440 nuclear power plants (NPPs) are operating in over 30 countries worldwide.

Depending on their type and characteristics, these NPPs generate over 200 thousand tons of high-level radioactive waste and millions of tons of low-level radioactive waste annually. While these figures may seem substantial, it is important to note that most of this waste has very low levels of radioactivity. There are specialized methods for safely storing and reprocessing this waste.

In conclusion, as nations navigate the complexities of energy production and environmental sustainability, the role of nuclear energy is likely to become increasingly prominent in the global energy mix.

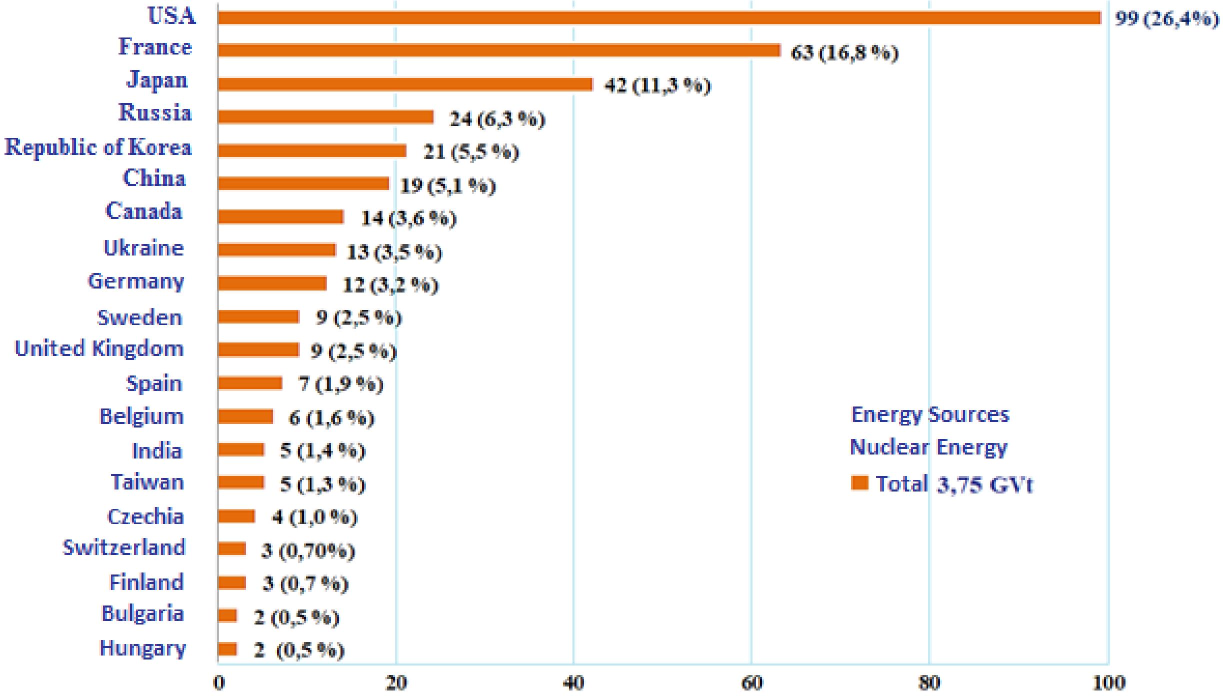

Figure 1. The number and capacity of nuclear power plants commissioned in developed countries.

Currently, the technological development of nuclear power plants (NPPs) has led to the emergence of modern, safe, and efficient types, with management processes transitioning to fully automated systems. Additionally, significant progress is being made in the recycling of nuclear waste, indicating the growth of the nuclear energy sector. The radioactive fuels used in these NPPs primarily consist of Uranium-235 and Plutonium-239.

In this context, we will examine the fission products generated during the fission of Uranium-235, particularly focusing on the elements Krypton (Kr), Strontium (Sr), Xenon (Xe), Ruthenium (Ru), and Iodine (I), along with their formation equations and the amounts of energy released. The fission reactions of these elements and their corresponding energy values are critical outcomes of the fission process of Uranium-235. The following calculations provide precise information about the products generated during nuclear fission in reactors and their energy release.

1. Formation of Krypton-92 (Kr-92): In the fission of Uranium-235, the isotope Krypton (Kr), for example, Kr-92, is produced through the following reaction:

$$^{235}_{92}U + n \rightarrow {}^{92}_{36}Kr + {}^{141}_{56}Ba + 3n + 200\ MeV$$

2. Formation of Strontium-90 (Sr-90): Strontium isotopes, such as Strontium-90 (Sr-90), are produced during the fission of Uranium-235 through the following reaction:

$$^{235}_{92}U + n \rightarrow {}^{90}_{38}Sr + {}^{144}_{54}Xe + 2n + 200\ MeV$$

This reaction illustrates how Uranium-235 undergoes fission upon absorbing a neutron, resulting in the formation of Strontium-90, Cerium-143, and additional neutrons, along with a significant release of energy.

Understanding the production of Strontium-90 and other fission products is crucial for assessing the safety and efficiency of nuclear power plants, as well as for managing nuclear waste effectively.

3. Formation of Xenon-135 (Xe-135): Xenon isotopes, such as Xenon-135 (Xe-135), are produced during the fission of Uranium-235. The process can be summarized as follows:

When Uranium-235 undergoes fission, it splits into various fission products, one of which is Xenon-135. The fission reaction can be represented as:

$$^{235}_{92}U + n \rightarrow {}^{135}_{54}Xe + {}^{98}_{38}Sr + 2n + 200\ MeV$$

In this reaction, Uranium-235 absorbs a neutron and subsequently undergoes fission, resulting in the formation of Xenon-135, Strontium-98, additional neutrons, and a significant release of energy.

Understanding the formation of Xenon-135 and other fission products is essential for evaluating the safety and efficiency of nuclear reactors, as well as for the effective management of nuclear waste.

4. Formation of Ruthenium-106 (Ru-106): Ruthenium isotopes, such as Ruthenium-106 (Ru-106), are produced through various nuclear processes, including fission reactions. The formation of Ru-106 can be described as follows:

Ruthenium-106 is primarily generated as a fission product during the nuclear fission of heavy elements, particularly Uranium-235 and Plutonium-239. When these heavy nuclei undergo fission, they split into several lighter nuclei, releasing energy and neutrons in the process. One of the isotopes produced in this reaction is Ru-106.

The fission reaction can be simplified as:

$$^{235}_{92}U + n \rightarrow {}^{106}_{44}Ru + {}^{131}_{53}I + 2n + 200\ MeV$$

In this reaction, Uranium-235 absorbs a neutron and subsequently undergoes fission, resulting in the formation of various fission products, including Ruthenium-106, along with the release of energy.

Understanding the formation of Ruthenium-106 and its behavior is crucial for assessing the safety and efficiency of nuclear reactors, as well as for managing nuclear waste effectively.

5. Formation of Iodine-131 (I-131): Iodine isotopes, such as Iodine-131 (I-131), are produced through various nuclear processes. The formation of I-131 can be described as follows:

Iodine-131 is primarily generated as a fission product during the nuclear fission of heavy elements, particularly Uranium-235 and Plutonium-239. When these heavy nuclei undergo fission, they split into several lighter nuclei, releasing energy and neutrons in the process. One of the isotopes produced in this reaction is I-131.

The fission reaction can be simplified as:

$$^{235}_{92}U + n \rightarrow {}^{131}_{53}I + {}^{102}_{38}Sr + 2n + 200\ MeV$$

In this reaction, Uranium-235 absorbs a neutron and subsequently undergoes fission, resulting in the formation of various fission products, including Iodine-131, along with the release of energy.

Understanding the formation of Iodine-131 and its behavior is crucial for assessing the safety and efficiency of nuclear reactors, as well as for managing nuclear waste effectively.

The energy released from the fission of a single Uranium-235 (U-235) atom is typically around 200 MeV. The resulting nuclear waste products, such as Barium-144 (Ba-144) and Krypton-92 (Kr-89), present significant challenges for processing. The short half-lives of these isotopes—11.5 days for Ba-144 and 3.15 minutes for Kr-89—complicate the waste management process due to their high radioactivity and the difficulty of separating them based on their chemical properties.

Nonetheless, these elements are being processed through transmutation and separation methods. The transmutation method involves irradiating radioactive isotopes with neutrons, transforming them into other radioactive elements via nuclear reactions. In the separation method, radioactive waste is divided into various elements, allowing the separated isotopes to be either processed further or safely stored.

When Plutonium-239 (Pu-239) is used as fuel, the resulting nuclear waste varies widely in composition and quantity, depending on the amount of Pu-239, the type of reactor, and operational conditions. This waste includes isotopes such as Plutonium-240 (Pu-240), Plutonium-241 (Pu-241), Americium-241 (Am-241), Curium-242 (Cm-242), Curium-244 (Cm-244), as well as fission products like Strontium-90 (Sr-90), Cesium-137 (Cs-137), Iodine-131 (I-131), Technetium-99 (Tc-99), and Chlorine-36 (Cl-36).

Currently, the recycling and utilization of these wastes are being explored to develop new materials and enhance applications in nuclear medicine. In the field of nuclear medicine, several radioactive isotopes are widely used, including:

Technetium-99 (Tc-99): Due to its versatile properties, Tc-99 is employed in scanning various organs and tissues in humans, making it one of the most commonly used radioactive elements in medicine.

Iodine-131 (I-131): This isotope is utilized in the treatment of thyroid diseases. Its radioactivity helps eliminate thyroid tumors, thereby halting the progression of these conditions.

Strontium-90 (Sr-90): This isotope is widely used in the treatment of cancer cells, including lymphoma, melanoma, bone cancer, and other types of malignancies.

Fluorine-18: Used in Positron Emission Tomography (PET) scans, this isotope plays a crucial role in diagnosing cancer, heart diseases, and neurological disorders.

Samarium-153: This isotope is effective in treating bone cancer and alleviating bone pain.

The demand for these isotopes is linked to their effectiveness, safety, and significant role in medical applications. Their use in medicine greatly aids in disease detection, treatment, and monitoring.

The physical, chemical, and biological properties required for these elements vary widely depending on their application areas, necessitating a diverse array of radionuclides. Consequently, numerous types of reactions are employed to produce them. Based on production technology, radionuclides can be categorized into those obtained through reactions involving accelerated ion beams in cyclotrons and those produced via neutron interactions in reactors.

Table 1 presents the primary reactions utilized in nuclear medicine.

Table 1. In the production of some medical and technological radionuclides reactions under the influence of neutrons.

Reaction	Nuclide	T_(1/2)	Field of application
$^{50}Cr(n,\gamma)^{51}Cr$	^{51}Cr	28 day	Medicine (diagnosis)
$^{58}Fe(n,\gamma)^{59}Fe$	^{59}Fe	46 day	Medicine (diagnosis), biology
$^{59}Co(n,\gamma)^{60}Co$	^{60}Co	5,27 year	Medicine (light therapy), sterilization
$^{74}Se(n,\gamma)^{75}Se$	^{75}Se	120 day	Biology, food production
$^{102}Pd(n,\gamma)^{103}Pd$	^{103}Pd	17 day	Medicine (diagnosis)
$^{130}Te(n,\gamma)^{131}Te \rightarrow {}^{131}I$	^{131}I	8 day	Medicine (therapy), diagnosis
$^{124}Xe(n,\gamma)^{125}Xe \rightarrow {}^{125}I$	^{125}I	59,4 day	Medicine (therapy), diagnosis
$^{152}Sm(n,\gamma)^{153}Sm$	^{153}Sm	47 s	Medicine, radiopharmacology
$^{164}Dy(n,\gamma)^{165}Dy$	^{165}Dy	2 s	medicine (therapy)
$^{165}Ho(n,\gamma)^{166}Ho$	^{166}Ho	26 s	Medicine (therapy), diagnosis
$^{168}Er(n,\gamma)^{169}Er$	^{169}Er	9,4 day	Medicine, radiopharmacology
$^{168}Yb(n,\gamma)^{169}Yb$	^{169}Yb	32 day	Medicine (diagnosis)
$^{176}Yb(n,\gamma)^{177}Yb \rightarrow {}^{177}Lu$	^{177}Lu	6,7 day	Medicine (b-therapy), diagnostics
$^{185}Re(n,\gamma)^{186}Re$	^{186}Re	3,8 day	Medicine (b-therapy), diagnostics
$^{188}W \rightarrow {}^{188}Re$	^{188}Re	17 s	Medicine (b-therapy)
$^{191}Ir(n,\gamma)^{192}Ir$	^{192}Ir	74 day	Medicine (b-therapy)
$^{197}Au(n,\gamma)^{198}Au$	^{198}Au	2,7 day	Medicine (therapy), diagnosis

In recent years, one of the modern diagnostic methods that has gained significant traction in medicine is Positron Emission Tomography (PET). This technique is based on the use of short-lived radioisotopes.

PET, also known as two-photon emission tomography, allows for the examination of the internal organs of humans and animals through radionuclide imaging.

Nuclear radiations are also widely used in medicine as a form of treatment. This method is referred to as radiation therapy. It is considered a primary tool in the treatment of malignant tumors.

Overall, these advanced imaging and treatment techniques highlight the important role of nuclear medicine in contemporary healthcare, providing precise diagnostics and effective therapeutic options for various medical conditions.

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