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Chapter

Nuclear Fuel Transmutation

Akbar Abbasi

Abstract

Nuclear power plants to generates electric energy used nuclear fuel such as Uranium Oxide (UOX). A typical VVER−1000 reactor uses about 20–25 tons of spent fuel per year. The fuel transmutation of UOX fuel was evaluated by VISTA computer code. In this estimation the front end and back end components of fuel cycle was calculated. The front end of the cycle parameter are FF requirements, enrichment value requirements, depleted uranium amount, conversion requirements and natural uranium requirements. The back-end component is Spent Fuel (SF), Actinide Inventory (AI) and Fission Product (FP) radioisotopes.

Keywords: nuclear power plant, nuclear fuel, front end, back end, actinide inventory

1. Introduction

VVER −1000 (Water-Water Energetic Reactor-1000) is a type of pressurized water reactor with 1000 MW thermal power planned to generate a 330 MWe [1]. Production actinide consequently of using nuclear power reactors as electric energy source. Actinide Inventory (AI) elements cumulative in spent fuel (SF) and are a part of spent fuel that useable as MO_X fuel in nuclear power reactors. Recently, some researchers have been studied the actinide inventory in spent fuel of nuclear power reactors [2–4].

VISTA computer code is available for the calculation of nuclide inventories in spent fuel. The neutron transmutation (fission) of the long-lived actinide isotopes in SF with decay times on the order of millennia into fission products with decay times of a few hundred years would profoundly impact the problem of storing SF that confronts the expansion of nuclear power. For the actinides, the creation comprises of neutron catch or decay of a forerunner nuclide. Evacuation may comprise of neutron-actuated or unconstrained fission; neutron catch and radioactive decay [5].

The estimation of the response rates requires nuclide fixation and cross-area information, the neutron transition level and vitality range in the fuel. As the energy spectrum in the fuel is subject to the grid structure and arrangement, such counts include rehashed iterative answers for the range and cross-section. The degree to which this is completed relies upon the precision expected of the last arrangement. After every burnup span, the combined range is utilized to get the neutron cross-segments which are accordingly utilized for the count of the nuclide response rates. The focuses to be considered in making an assessment of the accessible strategies are:

- data of nuclide cross-section
- energy spectrum evaluation
- neutron flux level calculation during the irradiation
- burnup equations numerical solution.

The treatment of these amounts in the few elective codes has been analyzed [6].

2. Nuclear fuel cycle

Nuclear fuel cycle definition is the set of cycles to utilize nuclear materials and to restore it to conclusive state. The fuel cycle begins with the mining of unused atomic materials from nature and closures with the protected removal of utilized nuclear materials in nature. **Figure 1** shows the nuclear fuel cycle diagram by indicating main processes in a recycle mode.

The first step is mining in a nuclear fuel cycle. After this step the next step is milling prosses. The feed for mining and processing measure is U metal and the item is U_3O_8 concentrate, which is generally called yellowcake because of its shading and shape [7]. The third step is change term that alludes to the way toward purging the U concentrate and changing over it to the synthetic structure required for the following phase of the nuclear fuel cycle.

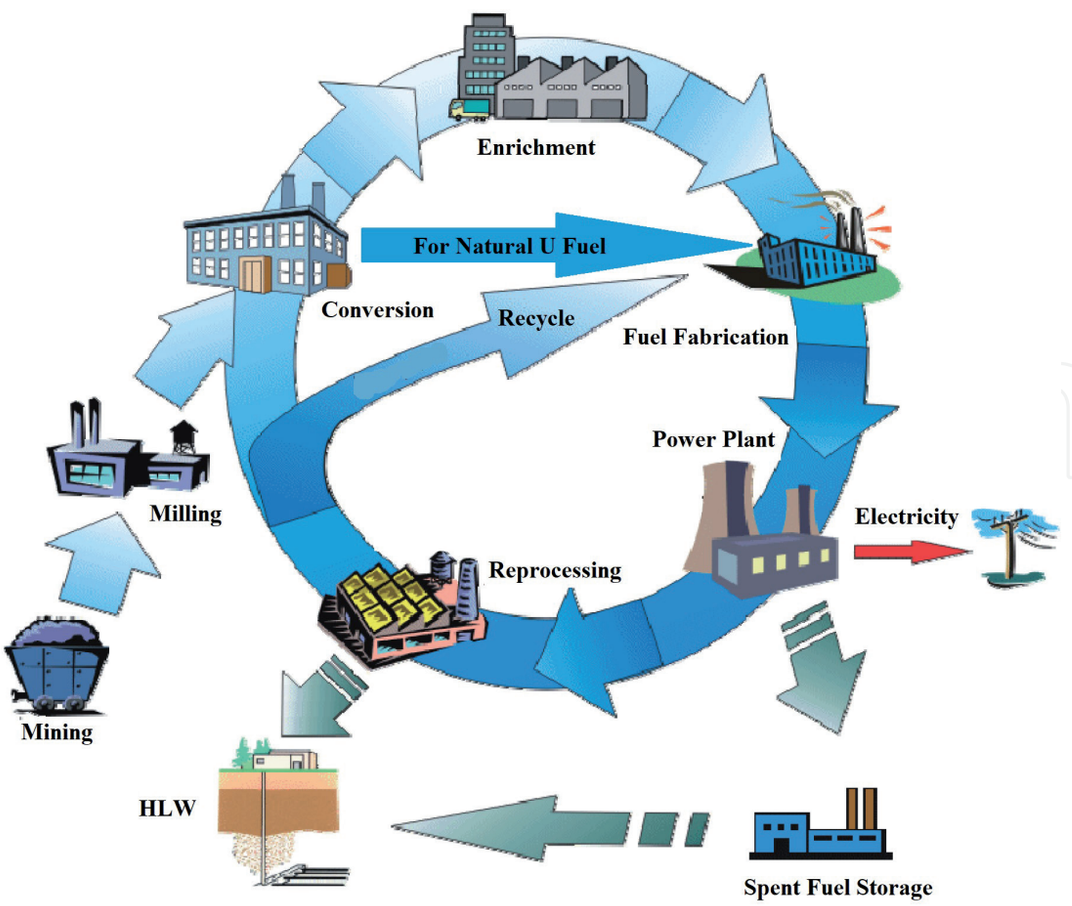

Figure 1.
The nuclear fuel cycle diagram.

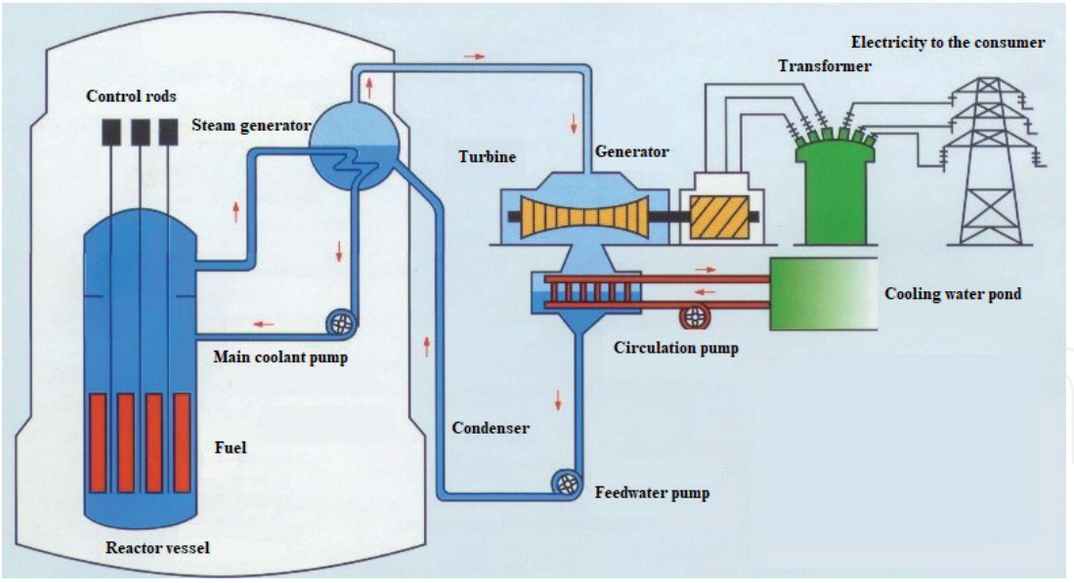

Figure 2.
Main components of a light water reactors (LWR) [8].

In this stage U element can be produced in three forms of metal, oxide (UO_2 or UO_3) and uranium hexafluoride (UF_6). UF_6 is the overwhelming item at this phase of the nuclear fuel cycle since it is handily changed over to gas for the advancement stage, as utilized on the planet's most regular reactor type. (LWRs) (see **Figure 2**).

The next process after conversion is enrichment step. In general, there are two industrially accessible advancement innovations: vaporous dispersion and rotator. The two strategies depend on the slight mass contrast somewhere in the range of ^{235}U and ^{238}U. Along these lines, the improvement is characterized as the way toward expanding the measure of ^{235}U contained in a unit amount of uranium. The feed for this stage is regular UF_6 and the item is enhanced UF_6. The other yield of the cycle is the uranium which has lower ^{235}U substance than the regular uranium. It is known as enhancement tail or exhausted uranium. Fuel fabrication is another term that the enrichment fuel was made as pellets. Fuel pellets are loaded into tubes of zircaloy or stainless steel, which are sealed at both ends. These fuel rods are spaced in fixed parallel arrays to form the reactor fuel assemblies (see **Figure 3**).

The whole process is referred as fuel fabrication. The reactor unit itself is irradiator for nuclear fuel. It burns the fuel, produces energy and spent fuel. The feed for reactor is new fuel containing U or U/Pu, if there should arise an occurrence of blended oxide (MOX) fuel, for existing atomic fuel cycle alternatives. The item is the spent fuel comprising of recently created nuclides, for example, splitting items (I. Cs, Sr, ...) minor actinides (Np, Am, Cm) and Pu just as the uranium. The greatest aspect of the spent fuel is still U (over 95% for the most reactor types). Reprocessing process is based on chemical and physical processes to separate the required material from spent nuclear fuel. The feed of this process is spent fuel and the products are reusable material and high-level wastes (HLW) [6].

The other unit of nuclear cycle fuel is spent fuel storage, which could be put away briefly for some time later or could be put away uncertainly. Spent fuel could be put away in pools (wet sort, briefly) or in storehouses (dry sort). Likewise, the loss from fuel manufacture and reprocessing offices are delegated HLW and requires cautious treating. HLW is put away in uncommon storerooms after legitimate treatment.

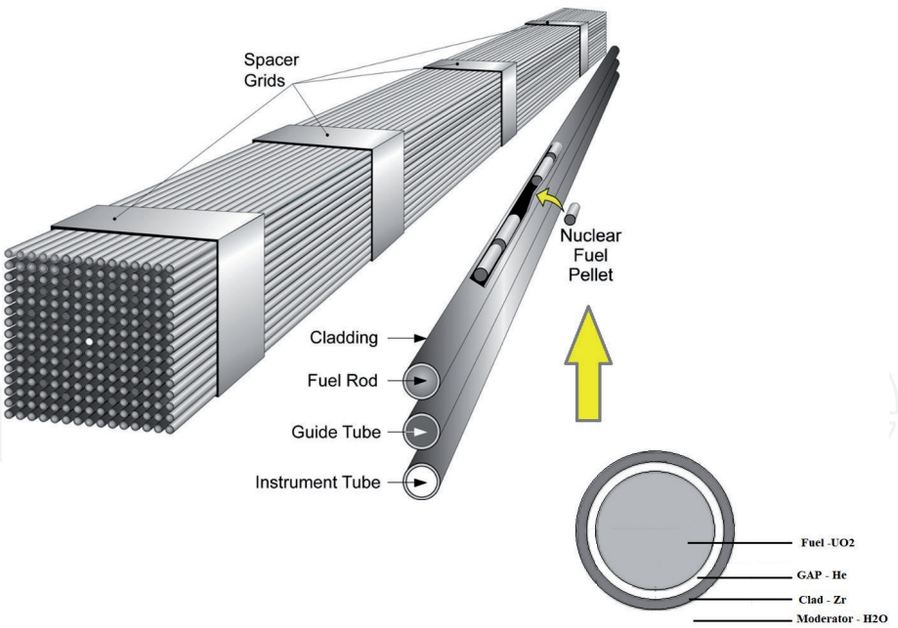

Figure 3.
The fuel fabrication [9].

3. The composition of transuranic in the spent fuel of VVER reactor

The following nuclides have been studied and the transmutation chain which is given in **Figure 4**. These radionuclides are: ^{235}U, ^{236}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{237}Np, ^{241}Am, ^{242m}Am, ^{243}Am, ^{242}Cm and ^{244}Cm.

The actinide transmutations to each chine are calculated by [10]:

$$\frac{dN_i}{dt} = -\sum_{i \neq j}\left[\lambda_{ji}^{d} + \sigma_{ji}^{tr}\varphi\right]N_i + \sum_{j \neq i}\left[\lambda_{ij}^{d} + \sigma_{ij}^{tr}\varphi\right]N_j \tag{1}$$

where N_i is atomic content of i^{th} –isotope; λ_{ji}^{d} is decay constant, (1/s); σ_{ji}^{tr} transmutation cross section from isotope i to isotope j, (barn) and φ is average neutron flux, (n/s·cm^2).

If the neutron flux and cross sections are constant on a time interval, the equation has a simple analytical solution.

An example to solve the transmutation chain starting from ^{238}U up to ^{240}Pu is shown below, using Bateman's Equation.

$$^{238}\text{U} \rightarrow ^{239}Pu \rightarrow ^{240}Pu \tag{2}$$

$$\text{AF}_1 \ldots \text{AF}_2 \ldots \text{AF}_3 \tag{3}$$

$$AF_1 = AF_1(initial).e\left(-\sigma_{t1}.\Phi.T.10^{-24}\right) \tag{4}$$

$$AF_2 = AF_1(initial).\left[\left(\frac{\sigma_{c1}}{\sigma_{t2}-\sigma_{t1}}\right).e^{-\sigma_{t1}.\Phi.T.10^{-24}} + \left(\frac{\sigma_{c1}}{\sigma_{t1}-\sigma_{t2}}\right).e^{e^{-\sigma_{t2}.\Phi.T.10^{-24}}}\right] \tag{5}$$

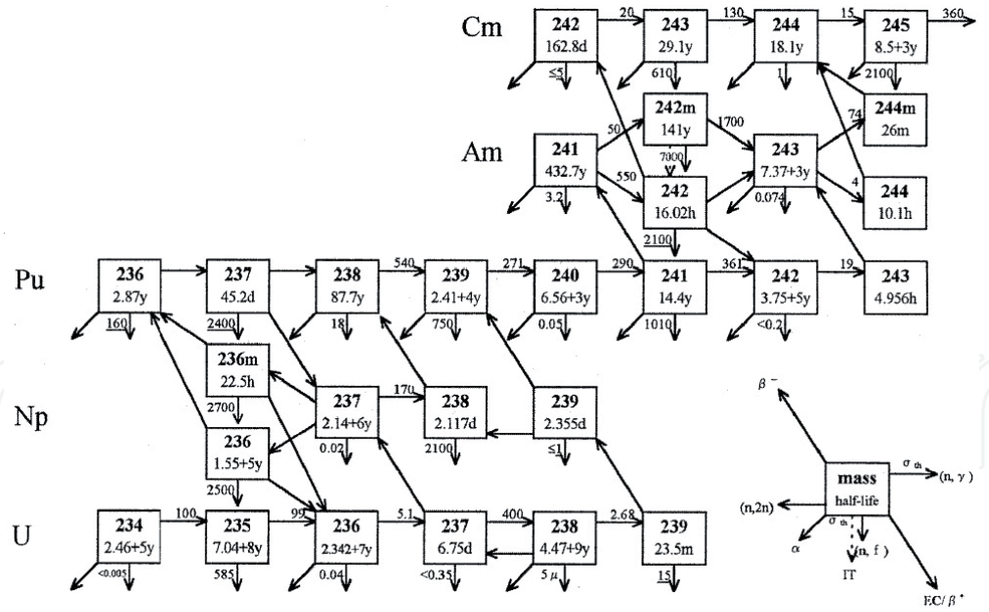

Figure 4.
The actinide transmutation chains [6].

$$AF_3 = AF_1(initial).\left[\left(\frac{\sigma_{c1}.\sigma_{c2}}{(\sigma_{t2}-\sigma_{t1}).(\sigma_{t3}-\sigma_{t1})}\right).e^{-\sigma_{t1}.\Phi.T.10^{-24}} + \left(\frac{\sigma_{c1}.\sigma_{c2}}{(\sigma_{t3}-\sigma_{t2}).(\sigma_{t1}-\sigma_{t2})}\right).e^{e^{-\sigma_{t2}.\Phi.T.10^{-24}}} + \left(\frac{\sigma_{c1}.\sigma_{c2}}{(\sigma_{t1}-\sigma_{t3}).(\sigma_{t2}-\sigma_{t3})}\right).e^{e^{-\sigma_{t3}.\Phi.T.10^{-24}}}\right] \quad (6)$$

where.

AF_i = Isotope(i) atomic content in the chain

σ_c = Cross-section of capture (barns)

σ_f = Cross-section fission (barns)

$\sigma_{n,2n}$ = Cross-section of (n,2n) (barns)

σ_{ex} = Cross-section of excited (barns)

σ_t = Cross-section totally (barns)

$$\sigma_{decay} = \frac{0.693}{T_{\frac{1}{2}}.365.24.3600.10^{24}.\Phi} \quad (7)$$

$$\sigma_t = \sigma_c + \sigma_f + \sigma_{ex} + \sigma_{decay} \quad (8)$$

$T_{1/2}$ = Half-life (years)

Φ = Neutron average flux (n/cm/cm/sec). (the energy range of 0 to 10 MeV total flux)

T = Time of irradiation (sec)

Radiation	Mass (u)	Charge	Range (air)	Range (tissue)
α	4	+2	~3 cm	~40 μm
β	$\frac{1}{1840}$	-1 or + 1	~300 cm	~5000 μm
X or gamma emission	0	0	Very large	Through body
Fast neutron (n)	1	0	Very large	Through body
Thermal neutron (n)	1	0	Very large	~15 cm

Table 1.
Properties of nuclear emission.

$$T = \frac{1000.E_d}{3600.KWKG.24} \tag{9}$$

E_d = Burnup discharge (GW·d/t)
KWKG = Specific power (MW/tonne)

The condition solver initially computes the isotopic piece in nuclear division. The acquired nuclear portions at that point are changed over to the weight divisions [6].

Nowadays, it is estimated that >2000 t of actinides has been accumulated as nuclear waste, most of which are plutonium isotopes. **Table 1** shows the composition of transuranic elements in the fresh and spent fuel of a VVER after recycling process [10]. The most significant commitment to the drawn-out radiation peril originates from ^{239}Pu (t½ = 24,110 a), from other Pu isotopes, and from other actinides, i.e., ^{237}Np (t½ = 2.1 × 106 a), ^{241}Am (t½ = 432 a), ^{243}Am (t½ = 7370 a) and ^{245}Cm (t½ = 8500 a) [11]. Pu and MA represent only 1.5% of the waste volume. Nonetheless, their radio toxicity becomes dominant after around 300 years and remains extensively high for a huge number of years, a period too long to even

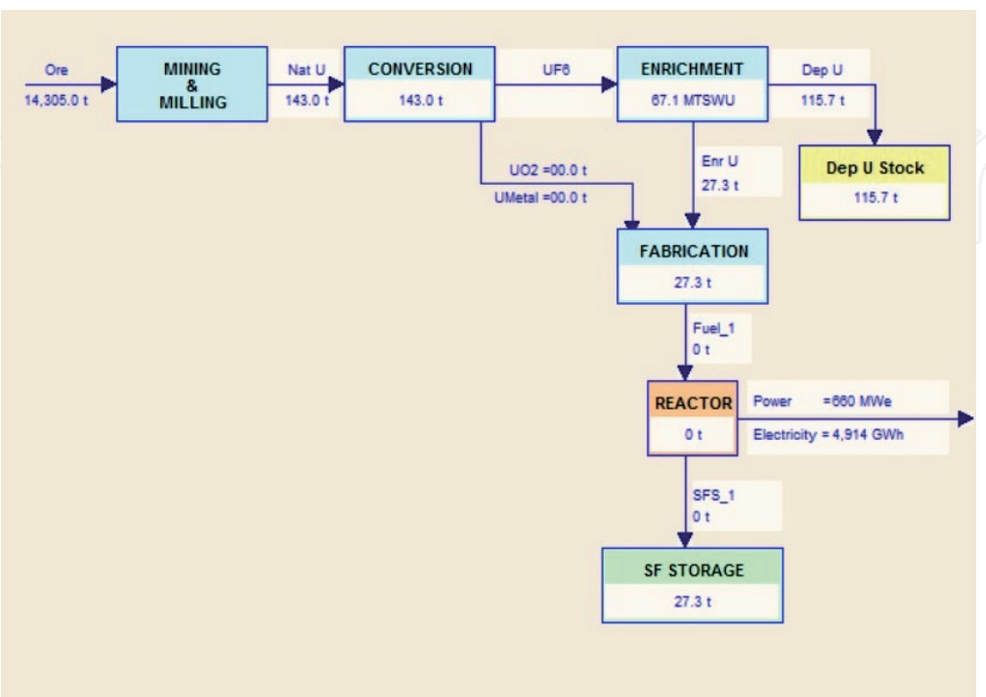

Figure 5.
The flowchart of nuclear material amounts calculated by VISTA.

consider guaranteeing a sheltered disengagement from nature by methods for building obstructions [12]. Besides, actinides present criticality and multiplication concerns. The fission cross-section of numerous actinides is portrayed by edges of a couple of 100 keV. Hence, they do not undergo fission in thermal reactors, rather reduce reactor critically as thermal neutron absorbers. However, they have significantly high fission cross-sections at high neutron energies [13].

The amount of nuclear materials for a VVER-1000 reactor was calculated and shown as diagram in **Figure 5**.

For VVER-1000 reactor, the fresh fuel, actinide elements and fission product values in spent fuel was calculated by VISTA simulation code.

The total amount of FF is 23.792 t/year with 22.915 t/year of ^{238}U and 0.877 t/year of ^{235}U. The grade of enrichment is 3.6% on average. The actinide martials content in SF of calculated by VISTA are ^{235}U (0.232123 t/year), ^{236}U (0.107850 t/year), ^{238}U (22.177277 t/year), ^{238}Pu(0.004352 t/year), ^{239}Pu(0.156181 t/year), ^{240}Pu(0.047959 t/year), ^{241}Pu(0.049525 t/year), ^{242}Pu(0.017008 t/year), ^{241}Am(0.001297 t/year), ^{237}Np(0.001239 t/year), ^{242m} Am(0.000019 t/year), ^{243}Am(0.003554 t/year), ^{242}Cm(0.000463 t/year) and ^{244}Cm(0.001142 t/year) radioelements. The values of above radioelements except ^{235}U and ^{238}U isotopes were compared in **Figure 6**.

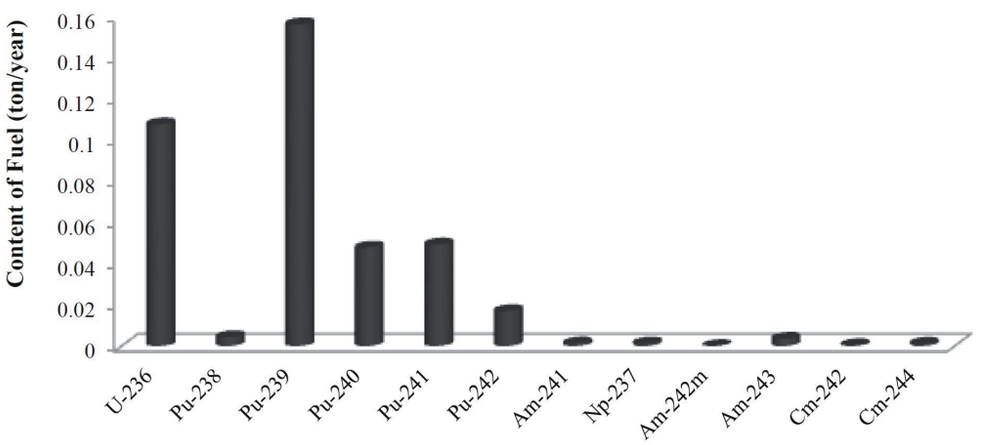

Figure 6.
The actinide elements content in spent fuel of the VVER-1000 reactor calculated by VISTA.

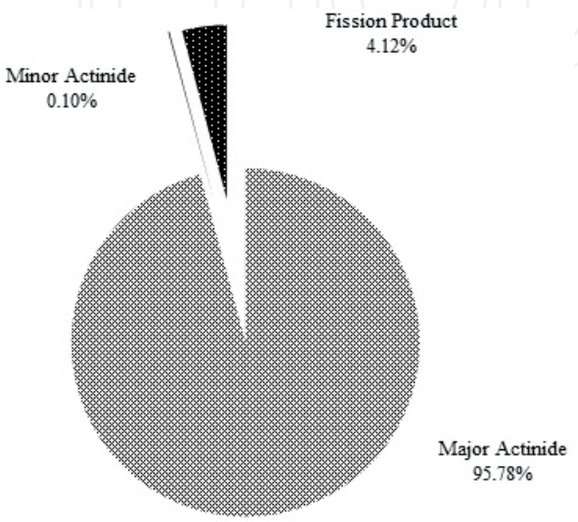

Figure 7.
Discharged UO_X spent fuel content in VVER-1000 reactor.

Also, the content of discharged UOX burned fuel in VVER-1000 nuclear power plant is presented in **Figure** 7.

4. Radiation and protection of nuclear fuel cycle

There are two type radiation sources naturally occurring radioactive materials (NORM) and technologically enhanced naturally occurring radioactive materials (TENORM) consist of materials in nuclear industry. The NORM radionuclides like ^{232}Th, ^{238}U, and ^{40}K that occur mostly in minerals such present all over the Earth's crust in varying quantities depending on the ambient geological end geochemical properties of local. NORM radioactive are present in soil [14–19], water [20–23] and building materials [24–30]. The TENORM materials is upset or changed from regular settings or present in a mechanically improved state due to past or introduce human exercises and practices, which may bring about a relative increment in radionuclide fixations, radiation presentations and dangers to people in general, and danger to the open condition above foundation radiation levels.

The properties and ranges of the various nuclear radiations are summarized in **Table 1**. The ranges are only approximate since they depend on the energy of the radiation [31].

The alpha particle has mass higher than beta particle, so these partials travels relatively slowly into matter. Alpha particle interaction is a high likelihood of with iotas along its way and will surrender a portion of its vitality during every one of these cooperation's. As an outcome, α particles lose their vitality quickly and travel without a doubt, extremely short separations in thick media.

Beta particles are a lot of littler than particles and travel a lot quicker. They consequently go through less associations per unit length of track and surrender their vitality more gradually than α particles. This implies β particles travel further in thick media than α particles.

Gamma radiation loses its vitality mostly by interfacing with nuclear electrons. It ventures enormous separations even in thick media and is hard to ingest totally.

Neutrons surrender their vitality through an assortment of collaborations, the general significance of which are reliant on the neutron vitality. Therefore, it is regular practice to separate neutrons into in any event three vitality gatherings: quick, moderate and warm. Neutrons are infiltrating and will travel enormous separations even in thick media.

An office ought to have set up a radiation assurance program that is satisfactory to secure the radiological wellbeing and wellbeing of laborers and the general population and guarantee that the presentations are ALARA. To achieve this, offices assess and describe the radiological hazard and regularly give adequate hearty controls to limit this danger. Potential mishap arrangements are considered in evaluating the ampleness of the controls, which expect to limit radiological danger and sullying.

The fuel cycle office radiation assurance rehearses incorporate [32]:

- A viable reported program to guarantee that word related radiological introductions are ALARA;
- An association with sufficient capability prerequisites for the radiation insurance work force;
- Approved composed techniques for directing exercises including radioactive materials;

- Radiation protection preparing for all faculty who approach limited zones;
- A program to control airborne convergence of radioactive material with building controls and respiratory insurance;
- A radiation overview and checking program that incorporates prerequisites for control of radioactive sullying inside the office and observing of outside and inward radiation presentations;
- Other projects to look after records, to report radiation introductions to the managing authority, and to restore an adequate in-plant radiological condition in case of an occurrence.

The execution of such projects with respect to coordinate radiation is currently made a lot simpler with the utilization of individual electronic dosimeters of Visa size that can immediately alarm the holder when momentary or cumulated portion reach modified edges, that keep in memory the historical backdrop of presentation and whose information can be downloaded to PCs, for instance each time the administrator enters or leaves the controlled zone, so these information can be naturally recorded and investigated. In this manner, point by point presentation previsions can be checked versus real introductions, permitting improvement of both working techniques and previsions. The improvement of mechanized screens that permit the perception of portion rates is likewise an incredible asset for radiation protection.

5. Conclusions

The content of this chapter is overall reviewing the nuclear fuel transmutation discussion. For this purpose, the nuclear fuel cycle of UOx type fuel was presented. In the next section the composition of transuranic in the spent fuel of VVER reactor was survived. Also, the amount of minor actinide and fission product in a VVER-1000 reactor was calculated and finally, the radiation protection principles of nuclear fuel cycle were presented and discussed.

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Conflict of interest

The authors declare no conflict of interest.

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