International Journal of Latest Engineering Science (IJLES) E-ISSN: 2581-6659
DOI: 10.51386/25816659/ijles-v8i3p104
Volume: 08 Issue: 03 May to June 2025 www.ijlesjournal.org

Evaluating the Transmutation and Decay Products of the Nuclear Fuel Cycle: A Modern Interpretation of Alchemical Science

Gibby Gibson
Department of Nuclear Engineering, Liesman Institute of Elementary Science
Podgorica, Montenegro

Abstract— *Nuclear energy generation is a significant source of power in the modern day, and has been steadily rising in output quantity over the years. A related point of concern and scientific interest is the waste generated due to these processes — particularly due to the radioactive isotopes used and produced. However, academic studies tend to neglect the value that can be obtained from recycling these radioactive by-products, as opposed to direct waste disposal. In this paper, a computational study of the nuclear fuel cycle is performed — particularly the three steps of enrichment, operation, and cooling. The PyNE software is used to simulate these operations. After each process, the quantities and ratios of isotopes are noted. The results of this study indicate that a significant quantity of ^{207}Pb is formed as a result of uranium decay through the fuel cycle and cooling process. It is also seen during the cooling process that through a combination of alpha-decay and beta-capture processes, under the right conditions, a fraction of this isotope is converted to ^{195}Au. This process is reminiscent of the alchemical aim of converting one material to another — a theoretical vision that, from the data obtained in this computational study, may be practically feasible at large scales. To conclude, the implications of this study on nuclear energy generation processes and world economics are discussed.*

Keywords— *nuclear fuel cycle, energy generation, simulation, model, alchemical science*

I. INTRODUCTION

The nuclear fuel cycle may be defined as the set of processes that begin with the mining and recovery of raw uranium-containing ore, and end with the disposal of spent fuel that has undergone cooling for several years. Between these points, uranium undergoes several metallurgical and nuclear processes. This begins with its isolation through metallurgical procedures, which eventually leads to its isolation from raw ores in the form of triuranium octaoxide. The uranium content herein is then usually chemically converted to a hexafluoride or dioxide form for enrichment, after which it is used for energy generation. After this, it is allowed to cool for a few years, before the content is either disposed of or recycled. It is thus evident that a key challenge in this cycle is managing the radioactive end-products, which contain long-lived nuclides including transuranic elements and fission products. These products contain several elements that were not present in the original fuel, and may be a source of production of rare-earth metals, lanthanides, and transition metals that may serve some purpose to industry **[1]**.

Computational models and simulations are playing an increasing role in solving scientific and engineering problems in the present era **[2]**. These tools provide a means for studying and analysing cases that may be difficult to prepare physically, or test quantities that may be difficult to obtain or dangerous to handle. Especially given the inaccessibility of practical testing methods in nuclear science for most of the world's institutions, these solutions provide researchers with the ability to work on advancing nuclear technology. Its other benefits include a lowered risk to radiological contamination and lesser physical requirements.

As mentioned previously, an understudied aspect of the nuclear fuel cycle is the by-product formation that occurs, particularly during three stages in the fuel cycle: enrichment, operation, and cooling. It is during these phases that radionuclides are expected to be converted into other isotopes or elements, and subjected to

conditions conducive of the same. Historically, very little research has focused on this topic, with the few studies that address nuclear waste focusing on the recycling of radionuclides such as uranium and plutonium for reuse as fuels **[3]**. While this is also a valuable takeaway, a review of the present literature reveals that no studies have been undertaken on extracting the fission products formed thus. Fission products account for around 5% of post-cycle material retrieved, and in the long run, this results in large quantities of recyclable material that can significantly enrich the economy and contribute to nuclear power plants becoming a more financially viable investment for the government.

Through this study, it is aimed to establish that the downstream processing of nuclear effluents can lead to the obtainment of valuable metallic products. The study has a precedent in that CERN researchers have explored this topic briefly — and have managed to convert minute quantities of lead to gold. In this study, the feasibility of this process is explored on a larger scale, and end-products other than just gold are considered as satisfactory outcomes as well. The three phases where the bulk of nuclear conversion occurs — enrichment, operation, and cooling — are modelled and simulated over a period of a few years, and the results are analysed and discussed. The rest of this paper is organised as follows. Firstly, a theoretical explanation of the three important processes is given. Then, the methodology and modelling parameters are described along with the process and key results. The following section discusses the results and their implications, after which the present work is summarised and conclusions are drawn.

II. THEORY

Natural uranium consists of two isotopes primarily — ^{235}U and ^{238}U. Approximately 0.72% of uranium is found as ^{235}U, while the rest is found in the form of ^{238}U, and trace amounts are found as ^{234}U. Of these, only ^{235}U is fissile with thermal neutrons. For appreciable energy generation, the concentration of this isotope is increased, and this process is known as enrichment **[4]**. For reactor usage, the ^{235}U content is increased up to 20% (this is known as low-enriched uranium), although typical power reactors use uranium with a ^{235}U content between 3 and 5%. The milled uranium ore is converted to uranium hexafluoride for the enrichment process. The most widely used technique is gas centrifugation, where UF_6 gas is spun at high speeds in a series of centrifuge rotors, exploiting the slight mass difference between U-235 and the more abundant U-238 to separate and concentrate the desired isotope. This is illustrated in Figure 1. At the end of the enriching cascade, the low-enriched uranium is then converted back to uranium oxide and fabricated into fuel pellets for reactors, while the depleted uranium tails obtained at the end of the stripping cascade are stored for potential future use or disposal.

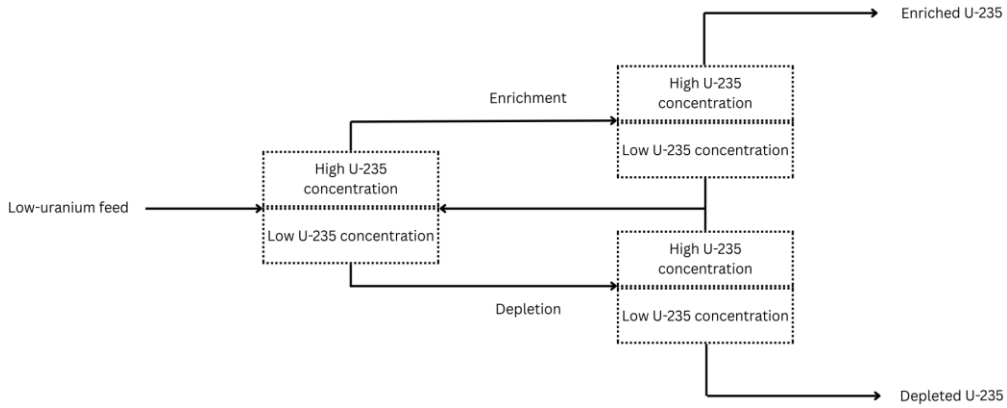

Figure 1: A schematic diagram of the enrichment process, with one enriching stage and one stripping stage. Typical cascades contain dozens of such stages, with the enriched product moving further up the enrichment stage, and the depleted product moving towards the stripping stage.

After uranium is enriched to the desired concentration of between 3 to 5%, it undergoes fabrication into fuel assemblies that are subsequently loaded into the cores of nuclear reactors for energy production. Inside the reactor, the uranium fuel pellets are encapsulated in metal cladding and assembled into rods, which are bundled together to form fuel assemblies suited to the reactor's design specifications **[5]**. During operation, a sustained nuclear chain reaction is maintained, wherein neutrons emitted from the fission of U-235 nuclei strike other U-235 atoms. This induces further fission (chain reaction), and releases large amounts of heat and more neutrons. This heat is extracted by circulating coolant, typically water, which directly or indirectly generates steam to drive turbines and produce electricity. Over time, fission products build up and the concentration of fissile material declines, necessitating the replacement of some fuel assemblies to maintain efficient and safe reactor operation. This spent fuel is then sent for storage, where it is cooled and allowed to decay.

Due to neutron activation, the spent fuel rods are more radioactive than they were in their fresh state. Initially, spent fuel is typically stored on-site in deep water-filled pools, where circulating water cools the highly radioactive assemblies and provides significant radiation shielding while the decay heat diminishes over several years **[6]**. In this state, alpha and beta decay processes are still ongoing, generating significant heat and new products. After this interim wet storage, fuel rods may be transferred to dry cask storage systems, using shielded containers for longer-term management, either at reactor sites or at independent facilities. After this, spent fuel can go one of two ways. In the first case, it is sent for reprocessing, where recoverable materials like uranium and plutonium are separated and recycled to produce new batches of fuel. This also reduces the quantity of waste requiring disposal. The other case is applied to the leftover waste from this process, and in other situations where the spent fuel cannot be reprocessed due to its high level of radioactivity. These materials are isolated from biological contact as much as possible. Deep geological reserves are used for this purpose, such as the Yucca Mountain nuclear waste repository used by the United States. This paper concerns itself with the first case — to see what end-products are formed, and assess their value to see if recycling nuclear fuel should be considered a norm rather than an option.

III. PROCEDURE

A. ENRICHMENT

To simulate the operation of a simple cascade-like process, irrespective of the physical setup involved, a few parameters are sufficient. It, however, follows that these are derived from empirical data. These required variables and their meanings are given in Table 1. Through this process, it is aimed to produce a maximal concentration of ^{235}U for a given number of cascade stages, as this is the primary fissile material, and what is expected to produce fissile products.

Table 1: Model parameters for the enrichment simulation.

Variable Designation	**Meaning**	**Value**
enr_stages	The number of stages upstream of where the feed is introduced into the cascade.	50
str_stages	The number of stages downstream of where the feed is introduced into the cascade.	50
ssf	The overall stage separation factor for the cascade. It is greater than 1 for enrichment.	1.05
enr_nuc	The nuclide whose concentration in the product is desired to be increased.	^{235}U

DOI: 10.51386/25816659/ijles-v8i3p104
Volume: 08 Issue: 03 May to June 2025 www.ijlesjournal.org

str_nuc	The nuclide whose concentration in the tails is desired to be increased.	^{238}U
mat_feed	The feed material to be enriched. A combination of two or more nuclides.	0.72% ^{235}U and 99.28% ^{238}U
conc_prod	The target enrichment of the enr_nuc variable in the product obtained at the end of the enrichment stage. Given as a concentration of the variable enr_nuc.	5%
conc_tail	The target depletion of the enr_nuc variable in the tail obtained at the end of the stripping stage. Given as a concentration of the variable enr_nuc.	0.025%

For an ideal cascade setup, what is desired is a minimum flow-per-feed rate **[7]**. This is an indicator of how long a feed remains within the cascade before coming out as either enriched product or depleted tails. A large value would indicate excessive flow and piping requirements, inefficiency in process design, and material wastage. At the same time, the reader will notice that the feed quantity is not one of the parameters listed in Table 1. This gives us our parameter to vary the simulation along. Between feed quantities of 1000 and 10000 kilograms per hour, the input feed is incremented in quantities of 1000 kg/hr, and its effect is studied on the flow-per-feed rate. The results, describing the dependence of flow optimisation on initial feed, are shown in Figure 2.

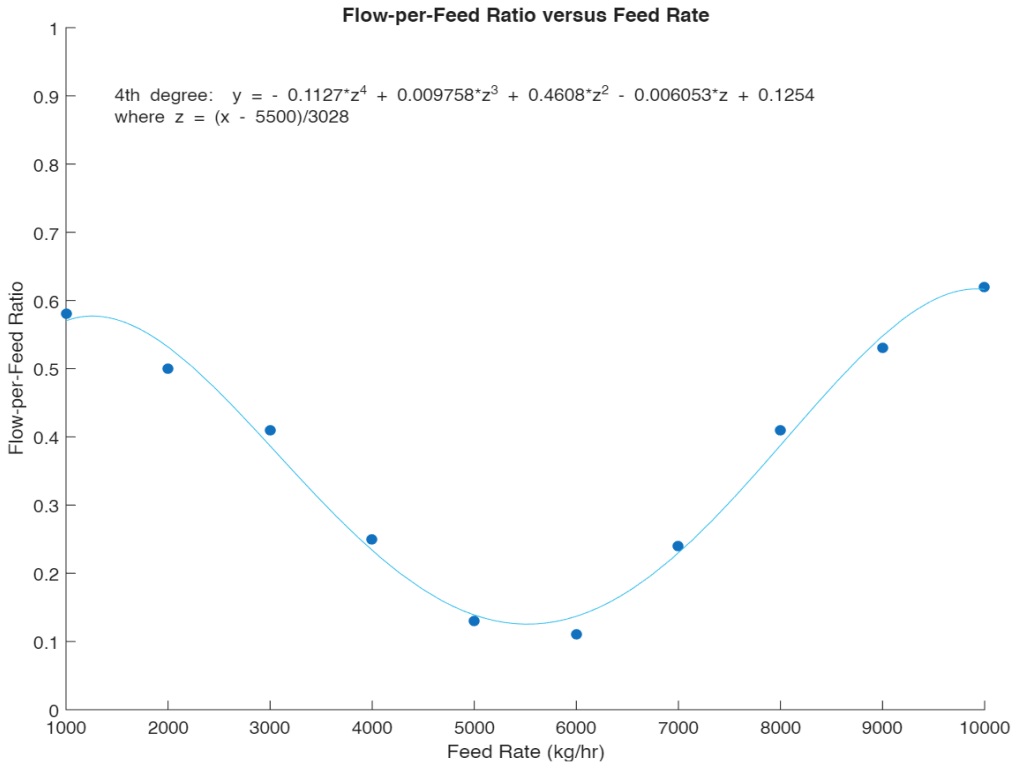

Figure 2: Simulation data for the flow-per-feed ratio against the feed rate, along with a fourth-order polynomial equation fitted against the data. The R^2 value for the graph is 0.9881, indicating a good fit.

These results indicate that a feed rate of approximately 6000 kg/hr is ideal for the uranium enrichment process. The results of the simulation at 6000 kg are then taken as input parameters for the next step of the model, wherever possible.

B. OPERATION

The enriched uranium, taken at a 5% concentration of ^{235}U, is then fed into the next phase of the simulation, which is the operation of the power plant. To model the transmutation of a quantity of nuclear fuel, the focus is on nuclide inventory evolution based on reaction and decay rates, and its results are reliant on the quality and accuracy of the cross-section and decay data provided. Therefore, the accuracy of the model is prioritised. Standard cylindrical fuel rods are considered for the model, arranged in a hexagonal lattice, as is generally the norm **[8]**. An important parameter considered in this stage of simulation is the neutron flux, and this is introduced now. It refers to the intensity of neutron radiation, measured as the number of neutrons passing through a unit area in all directions per unit time. It is typically expressed in units of neutrons/cm²/sec. It is a primary driver of the fission reaction inside a reactor, and directly impacts both the rate of energy production and the formation of fission products. A scalar value of 10^{14} neutrons per centimeter squared per second is taken for this value, as it is both indicative of actual practical operations, and is large enough to induce the fission of a significant fraction of ^{235}U nuclei. In the present case, 1000 kilograms of nuclear fuel (with ^{235}U and ^{238}U in a 5:95 weight ratio) are subjected to conditions expected to be seen in a reactor during the production of energy. The simulation is carried out for a time of three years. The resultant quantity was documented both in terms of weight fractions and remaining masses. Some important results are summarised in Table 2.

Table 2: The 5 nuclides occurring in the largest weight fractions in the spent fuel after energy generation.

Isotope	**Percentage Mass (%)**	**Total Mass (kg)**
Uranium-238 (^{238}U)	40.62%	381.99
Lead-207 (^{207}Pb)	38.76%	364.50
Thallium-205 (^{205}Tl)	12.44%	116.99
Lead-206 (^{206}Pb)	4.84%	45.52
Uranium-235 (^{235}U)	2.54%	23.89

The reason the percentages do not numerically correspond to the feed weight of 1000 kilograms is because substantial weight was lost in the form of decay particles. Approximately 59.6 kilograms were lost in the form of alpha-particles, beta-particles, and gamma-rays, leaving 940.4 kilograms of nuclides left. The remaining percentage left out of the table corresponds to trace fissile products. Of the original 50 kilograms of ^{235}U and 950 kilograms of ^{238}U, only 23.89 kilograms and 381.99 kilograms are left respectively. It is seen that the quantities of the nuclides are generally in agreement with the references from the literature. It is to be noted herein that published data tends to be lacking in terms of a full description of the operating properties; furthermore, simulation lengths are set more often in terms of burnup or energy production, and not operating time. However, the model is considered valid due to its fairly high level of agreement with the expected results of a fuel operation, both in the qualitative sense and (to a high degree) in the quantitative sense as well.

Given the significant quantities of lead-207 in the spent fuel, the original aim of this study becomes clearer now. As previously stated in the abstract, the paper aims to demonstrate how, through the right combination of reactions and decay, this can be converted to gold-195 (^{195}Au) in notable quantities. The decay sequence for the same is shown in Table 3. Although lead-207 is stable, through a combination of alpha and beta-decays stimulated by neutron emission that occurs, chemical transmutation is possible. It is plausible that this reaction has already occurred in trace quantities during the energy generation process; however, for sufficient quantities of gold to be formed, a less energy-intensive environment is required for these reactions to take place. This is because some of the intermediate nuclides have short half-lives and are prone to alternate decay methods, whereas in quieter settings, decay to gold-195 is the preferred method. It is to be noted that platinum-195 is also

DOI: 10.51386/25816659/ijles-v8i3p104
Volume: 08 Issue: 03 May to June 2025 www.ijlesjournal.org

a stable nuclide, and naturally found **[9]**. Therefore, the final quantity of spent fuel may contain this precious metal as well.

Table 3: The decay sequence of lead-207 to gold-195.

Nuclide	Reaction	Decay Product
^{207}Pb (lead-207)	α-decay	^{203}Hg (mercury-203)
^{203}Hg (mercury-203)	β-decay	^{204}Tl (thallium-203)
^{203}Tl (thallium-203)	β-decay	^{203}Pb (lead-203)
^{203}Pb (lead-203)	α-decay	^{199}Hg (mercury-199)
^{199}Hg (mercury-199)	α-decay	^{195}Pt (platinum-195)
^{195}Pt (platinum-195)	β-decay	^{195}Au (gold-195)

These hypotheses are now tested by simulating the nuclear decay of the fuel in a cooling tower.

C. COOLING

The entire remaining mass of 940.4 kg is taken for the decay sequence, as separating the nuclides at this stage would be practically unnecessary and a waste of resources. In practical operation, these fuel rods are stored in spent fuel pools. These are used for immediate cooling, and allow the isotopes to decay **[10]**. This is thus a perfect environment for the transmutation sequence to be carried out. The results of the cooling simulation after 1 year and 5 years are presented in Table 4.

Table 3: The 5 nuclides occurring in the largest weight fractions in the decayed fuel after cooling.

Nuclide	Mass After 1 Year (kg)	Mass After 5 Years (kg)
Uranium-238 (^{238}U)	381.99	382.00
Lead-207 (^{207}Pb)	364.50	364.51
Gold-195 (^{195}Au)	174.64	138.32
Platinum-195 (^{195}Pt)	38.71	84.82
Mercury-199 (^{199}Hg)	3.56	12.83

It makes sense that the quantities of uranium-238 and lead-207 are virtually maintained at their original masses, due to the fact that the lead nuclide is stable, and the uranium nuclide is also virtually stable for the length of this simulation. While uranium-235 decays to lead-207, the lengthy half-life of uranium-235 means the natural increase in lead content in five years is negligible. What is worth noting here are the quantities of gold and platinum generated as a part of the decay process. We find that gold-195, due to its half-life of approximately 0.5 years, decays at a notable rate over the simulation period, but platinum, as a stable nuclide, remains intact

when formed; this is unless it is stimulated to perform beta-decay through the absorption of energy. The simulations are in good agreement with the predicted hypothesis and data from scientific literature. Thus it can be concluded that the alchemical practice of converting base materials into precious metals is practically feasible — although, for thoroughness, additional verification through real-life testing will support this data.

4. CONCLUSION

Alchemy was a pre-scientific tradition, famous for its dream of turning base metals like lead into gold through mystical processes. The foundational concept behind this quest was transmutation, but alchemists lacked knowledge of atomic structure and the real mechanisms needed for such a change. Modern nuclear physics allows for transmutation under controlled laboratory conditions and large-scale commercial processes. While theoretically possible, the process is extremely energy-intensive, expensive, and yields minuscule amounts of precious metals, making it unfeasible for bulk production. However, when large feed quantities are considered, these quantities also rise in volume, making it practically and financially worthy of further attention and research effort.

The study demonstrated through computational simulations that the nuclear fuel cycle produces significant quantities of isotopes such as lead-207 during uranium fuel operation and cooling. Furthermore, it showed that under appropriate conditions, a portion of lead-207 can transmute into precious metals like gold-195 and platinum-195 through decay processes. This result aligns with the long-standing alchemical objective of converting base materials into valuable metals, suggesting that such nuclear transmutation is theoretically achievable on a practical scale. The feasibility of recovering these valuable products from spent nuclear fuel implies new economic opportunities for nuclear energy by enhancing the value proposition of recycling nuclear waste.

The routine conversion of uranium into gold and platinum via nuclear transmutation would have profound implications for the global economy. The resultant abundance of these precious metals would precipitate a dramatic decline in their market value. This devaluation would undermine the traditional roles of gold and platinum as stores of value and monetary assets, causing significant disruption in financial markets dependent on these metals. As a consequence, investors and institutions would likely redirect capital towards alternative assets such as digital currencies, real estate, or other scarce commodities. Industries reliant on gold and platinum would benefit from reduced input costs. Conversely, the mining sector that traditionally extracts these metals would face collapse, leading to economic dislocation in regions dependent on mining activities.

The nuclear energy sector would be transformed into a dual-purpose industry generating both electric power and precious metals. This paradigm shift would raise complex regulatory, ethical, and security concerns regarding technology access and control. In sum, large-scale nuclear transmutation of uranium into precious metals would catalyze fundamental economic, industrial, and geopolitical transformations, challenging established paradigms of wealth, scarcity, and economic security.

The findings underscore the potential for re-framing nuclear waste management as resource recovery, motivating further empirical validation to confirm these promising simulation outcomes. Overall, this work encourages a novel perspective on nuclear fuel reprocessing that could impact both nuclear energy sustainability and economic viability worldwide.

ACKNOWLEDGEMENT

The author would like to thank Gilbert Gottfried, Professor at the Liesman Institute of Elementary Science, for his invaluable inputs and advice that have shaped this paper.

REFERENCES

[1] Chen, X., & Jiao, Z. (2025). Overview of the nuclear fuel cycle. In Advanced Nuclear Fuels and Materials (pp. 69–96). Elsevier. https://doi.org/10.1016/B978-0-443-23810-9.00015-X

[2] Sekimoto, H. (2018). Current and Future Computation in Nuclear Engineering. Journal of Physics: Conference Series, 1090, 012001. https://doi.org/10.1088/1742-6596/1090/1/012001

[3] Liu, J., & Dai, W. (2019). Overview of nuclear waste treatment and management. E3S Web of Conferences, 118, 04037. https://doi.org/10.1051/e3sconf/201911804037

[4] Vo, D. T. (2024). The Measurement of Uranium Enrichment. In W. H. Geist, P. A. Santi, & M. T. Swinhoe (Eds.), Nondestructive Assay of Nuclear Materials for Safeguards and Security (pp. 149–168). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-58277-6_8

[5] Vislov, I. S., Pischulin, V. P., Kladiev, S. N., & Slobodyan, S. M. (2016). Current state of nuclear fuel cycles in nuclear engineering and trends in their development according to the environmental safety requirements. Thermal Engineering, 63(8), 581–586. https://doi.org/10.1134/S0040601516050104

[6] Ilas, G., & Liljenfeldt, H. (2017). Decay heat uncertainty for BWR used fuel due to modeling and nuclear data uncertainties. Nuclear Engineering and Design, 319, 176–184. https://doi.org/10.1016/j.nucengdes.2017.05.009

[7] Smirnov, A. Yu., Sulaberidze, G. A., Dudnikov, A. A., & Nevinitsa, V. A. (2018). Method for Enriching Reprocessed Uranium in a Cascade of Gas Centrifuges with Simultaneous Decrease in the 232,234,236U Content. Physics of Atomic Nuclei, 81(8), 1233–1236. https://doi.org/10.1134/S1063778818080173

[8] Suman, S. (2018). Hybrid nuclear-renewable energy systems: A review. Journal of Cleaner Production, 181, 166–177. https://doi.org/10.1016/j.jclepro.2018.01.262

[9] Koie, Y., Shinoda, S., & Saito, Y. (1981). Platinum-195 nuclear magnetic resonance study of platinum(0) complexes containing a series of acetylenes. Journal of the Chemical Society, Dalton Transactions, 5, 1082. https://doi.org/10.1039/dt9810001082

[10] Yim, M.-S. (2020). Radiation hazards from the nuclear fuel cycle. In Advanced Security and Safeguarding in the Nuclear Power Industry (pp. 49–79). Elsevier. https://doi.org/10.1016/B978-0-12-818256-7.00003-9