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A Study on the Timeframe for Mitigating Radiological Risk of Spent Nuclear Fuel from Direct Disposal Perspective

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1. Introduction

The safe and permanent management of spent nuclear fuel is a critical issue, given the significant amounts of long-lived radionuclides and high levels of heat and radioactivity emissions it contains. One potential solution for its safe disposal is deep geological repositories. Determining an appropriate time frame for conducting a comprehensive safety assessment of a repository and evaluating safety or performance indicators is crucial, as the evolution of both the disposal system and the environment can significantly vary over time.

Considering this background, the present study aims to assess the long-term persistence of radiological hazards associated with spent nuclear fuel. Specifically, the study examines the waste level of spent nuclear fuel, as well as the potential for external and internal exposure over time, while considering the necessary time frame for direct disposal of spent nuclear fuel.

2. Methods and Results

This section has provided a comprehensive review of the time horizons that are critical for evaluating spent nuclear fuel, including external exposure, internal exposure, and waste level. The Origen-arp code was utilized to evaluate waste levels and radiotoxicity, while the results of literature surveys were employed to assess external exposure.

2.1 External exposure

The Fig.1 illustrates the evaluation of external exposure dose rate at a distance of 1 meter from 1 ton of spent nuclear fuel by SKB. The results indicate that gamma radiation is the primary contributor to the exposure dose rate, whereas neutron dose accounts for less than 1% of the total dose. The external dose rate exceeds 10,000 mSv/hr by approximately 100 years, declines rapidly until the one thousand years, and remains above 10 mSv/hr thereafter. This reduction in dose rate is attributed to the decay of fission products present in the spent nuclear fuel, which leads to a significant decrease in gamma-ray emissions within a few hundred years of release. Moreover, the contribution of actinide nuclides to gamma-ray emissions is negligible, indicating that there is no substantial variation in external dose rates beyond a millennium.

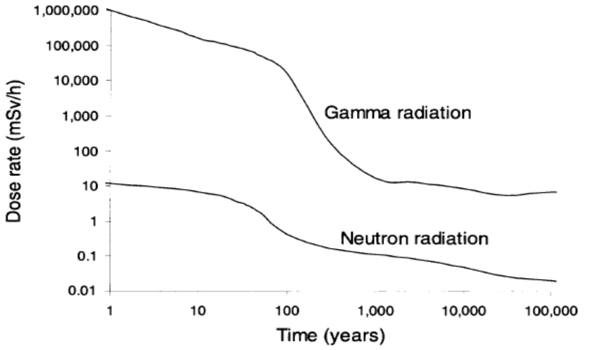

Fig.1. Dose rate at a distance of 1 meter from one ton of spent nuclear fuel at different times after discharge from the reactor [1]

Despite the rapid decrease in the external exposure dose rate from spent nuclear fuel over a few hundred years, the evaluated dose rate still greatly exceeds the effective dose limit set by the Nuclear Safety Act. According to the Enforcement Decree of the Nuclear Safety Act, the annual effective dose limit for the general public is 1 mSv, while for radiation workers, the limit is 100 mSv for five consecutive years, not exceeding 50 mSv/yr. The Standard on Radiation Protection, etc. of the NSSC Notification 2019-10 specifies that the tolerable dose for the general public within the annual dose limit is 0.1 mSv per week or 20 μSv per hour. Therefore, considering the risk of exceeding these dose limits, it would be impossible for both workers and the general public to access spent nuclear fuel for over hundreds of thousands of years.

Therefore, even with long-term storage, it is not possible for humans to handle spent nuclear fuel directly, and sufficient shielding must be applied to ensure that the external dose to workers is within legal requirements. In other words, the risk in terms of external exposure of spent nuclear fuel lasts for more than hundreds of thousands of years.

2.2 Internal exposure

Radiotoxicity is determined by the quantity of water needed to dilute the concentration of radionuclides below the ingestion limit, ensuring that direct ingestion of radioactive waste does not pose a threat. This measure is commonly utilized to estimate the duration necessary to reduce the radiological hazard of spent nuclear fuel to that of natural uranium. The radiotoxicity of Plus7 spent nuclear fuel is depicted in the fig.2, indicating that it takes around 200,000 years or more for the toxicity of spent nuclear fuel to diminish to the level of natural uranium.

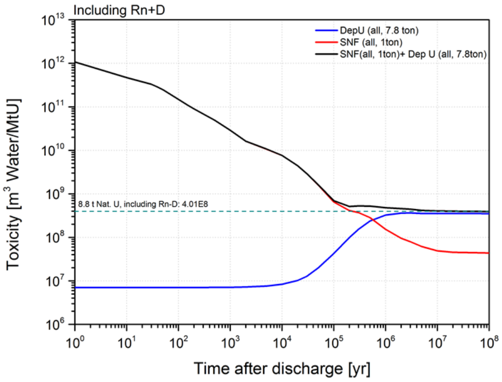

Fig.2. Radiotoxicity of ingestion of uranium ore (green dotted line) and all fractions resulting from the nuclear fuel cycle of the same quantity of uranium mineral (black line)

2.3 Waste level and concentrations of major nuclides

High-level waste is characterized by a radioactivity concentration of alpha-ray emitting nuclides with a half-life of 20 years or more greater than 4000 Bq/g, and a heat generation rate greater than 2 kW/m^3[2]. The Fig.3 displays the decay heat and radioactivity emitted by Plus7 PWR spent nuclear fuel divided by the threshold for classification as high-level waste. Cooling PWR spent nuclear fuel for about 300 years reduces the heat of decay below the high-level waste threshold. The Fig.4 illustrates the nuclide concentrations of the main nuclides in Plus7 PWR spent nuclear fuel divided by the threshold value for distinguishing between intermediate and low-level waste[5]. The concentrations of alpha nuclides and highly mobile and long-lived nuclides such as ^{137}Cs, ^{129}I, and ^{99}Tc exceed the reference values for hundreds of thousands of years or longer.

Although spent nuclear fuel may not meet the criteria for classification as high-level waste based on the reduction of its heat generation rate after a sufficient cooling period, it should be managed similarly to high-level waste due to the ongoing high concentrations of specific major nuclides. Furthermore, because intermediate-level waste and above cannot be disposed of in the surface disposal repository[5], spent nuclear fuel must be deposited in the deep geological repository, even after prolonged storage.

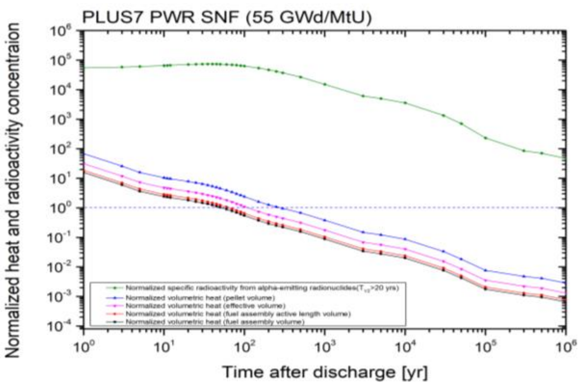

Fig.3. Normalized heat and radioactivity concentration [4]

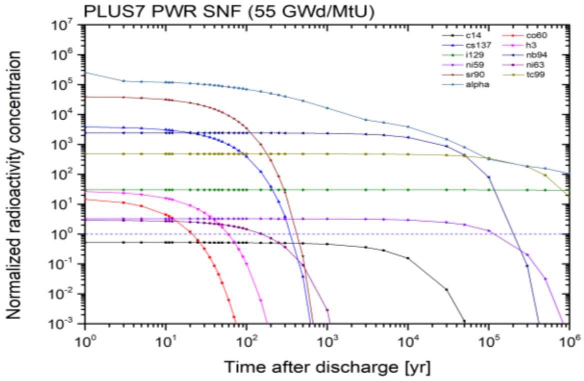

Fig.4. Normalized radioactivity concentration for major nuclides [4]

3. Conclusions

This study examines the long-term radiological hazards and waste levels associated with spent nuclear fuel, including both internal and external exposures. The high radioactivity of spent nuclear fuel persists for hundreds of thousands of years, which necessitates shielding during handling to meet external exposure regulations. Additionally, it takes hundreds of thousands of years for radiotoxicity to decay to natural levels of uranium. Although the heat generation rate eventually falls below the threshold for high-level waste, spent nuclear fuel still contains significant amounts of alpha nuclides and long-lived mobile radionuclides, which require disposal in a deep geological repository as intermediate-level waste or higher, even after hundreds of thousands of years. Therefore, it is crucial to consider the evolution of the disposal system and environment over hundreds of thousands of years when evaluating the long-term safety of the disposal system.

REFERENCES

[1] Allan Hedin, Spent nuclear fuel – how dangerous is it? A report from the project "Description of risk", SKB, March 1997

[2] Enforcement Decree of the Nuclear Safety Act

[3] Notice of NSSC (2019-10), Standards for Radiation Protection, etc.

[4] In-Young Kim, et.al, Analysis on characteristics of reference SNF for KRS+ Design – I. Plus7 SNF

[5] NSSC Notice (2020-06), Regulations on the Criteria for the Classification and Clearance of Radioactive Wastes