Possible Deep Geological Repository Site for High-Level Radioactive Waste in The Kingdom of Saudi Arabia – Saudi International Conference on Nuclear Power Engineering

Author Name(s)
Author:
Rayan Alahdal
Co-authors:
Moaid Balkhoyor, mohammed makki, Prof. Daud mohamad
Affiliation
King Abdulaziz university
Faculty of Engineering
Department of Nuclear Engineering
Address
King Abdulaziz University, Jeddah 21589, P.O.Box 80200, Phone: 800-11-69528
Email(s):
ralahdal0013@stu.kau.edu.sa
daudmohamad53@gmail.com
mzakari0004@stu.kau.edu.sa
moaid.jbb@gmail.com

Abstract – The accelerating growth of the population and the constant development of technology created a high energy demand. However, these involved factors increased energy consumption, therefore increasing the greenhouse effect, and triggering atmospheric pollutants. Thus, creating demand for a more sustainable and cleaner energy source, the role of nuclear energy emerged. The nuclear industry faced challenges revolving around waste management, where it needed advanced technology and detailed plans to dispose of the radioactive waste safely. This paper investigates the geology of the Kingdom of Saudi Arabia to site the first Deep Geological Repository (DGR). The geology of the kingdom looks promising for such big-scale projects. Using the GIS approach, it was found that the geology of the southern side of the kingdom seemed suitable for a DGR that centers within the Empty Quarter. The site meets the requirements of a DGR, such as rare possibilities of earthquakes, floods, stability, depth ranging up to 1000 meters, and the sedimentary geological formations. This paper contributes to the Saudi nuclear power program for the radioactive waste generated from research and industrial nuclear reactors following the 2030 vision to use nuclear and renewable energy resources.

Keywords: High-level Radioactive waste, waste management, Deep geological Repository, Nuclear Energy, Saudi Arabia Geology.

I. Introduction

The growing global population, rapid technological advancements, and the pursuit of space exploration have led to an exponential rise in energy demand. However, this increasing energy consumption has also accelerated greenhouse gas emissions, triggering environmental challenges like the greenhouse effect and atmospheric pollutants such as Carbon Dioxide (CO_2), Methane (CH_4), and nitrous oxide (N_2O) [*United States Environmental Agency, 2023*]. In the search for sustainable and cleaner energy sources, nuclear energy emerges as a prominent contender. Nuclear energy, harnessed through nuclear fission, is found naturally on Earth, the sun, and throughout the universe. Though the technology for nuclear fusion remains under development [*IAEA,2022*], nuclear fission is currently used to produce electricity globally.

Nuclear waste management and the nuclear fuel cycle constitute critical aspects of the nuclear power industry. The effective handling, storage, and disposal of radioactive waste materials are essential to safeguard human health and the environment from the hazards of radioactivity [*U.S. NRC,2020a*]. The nuclear fuel cycle encompasses a series of stages, commencing with the mining and milling of raw materials, such as uranium, which is crucial for nuclear fuel production. Conversion of extracted materials into Uranium Hexafluoride (UF_6) enables further processing for enrichment. The enrichment process involves increasing the concentration of fissile isotope ^{235}U from its natural abundance of 0.7% up to 3-5% for fuel fabrication by using several methods such as gaseous diffusion, gas centrifuge, and laser separation. Gaseous diffusion utilizes molecular diffusion through porous membranes, while gas centrifuge employs centrifugal force for isotope separation. Whereas, laser separation, an emerging method, employs lasers to selectively separate uranium isotopes [*U.S. NRC,2020b*]. Following enrichment, the deconversion process is employed to produce chemically stable compounds suitable for disposal as Low-Level Waste (LLW) [*U.S. NRC,2020c*]. The resultant uranium dioxide and depleted tri-uranium oct-oxide (U_3O_8) effectively reduce the hazard posed by depleted uranium waste. Moving ahead in the nuclear fuel cycle, fuel fabrication entails converting enriched uranium into nuclear fuel through various intricate processes. These include converting (UF_6) into Uranium dioxide (UO_2) powder, pressing it into pellets, and assembling it into fuel rods within Zircaloy tubes [*U.S. NRC,2023*]. The reactor operation stage facilitates controlled nuclear reactions, such as fission, to generate heat and electricity [*U.S. Energy Information Administration, 2023]*. However, after several years of operation, spent fuel management has become a critical concern. Spent fuel can be safely stored in either spent fuel pools or dry cask storage, ensuring radiation shielding [*World Nuclear Association,2022a*]. Furthermore, reprocessing of spent fuel is explored in countries like France, the United Kingdom, and Japan, aiming to extract valuable materials and reduce radioactive waste volume. Uranium and plutonium reprocessing processes are elucidated, highlighting their significance in potential fuel reuse [*World Nuclear Association,2017*]. Remaining radioactive waste must be safely stored and disposed of, with approaches including surface, near-surface, deep disposal, and borehole methods.

Radioactive waste produced during the nuclear power plant fuel cycle can be categorized into three forms: gaseous, liquid, and solid. Gaseous waste is primarily released during spent fuel reprocessing, while liquid waste results from cleaning and maintaining radioactive reactor coolant and systems, requiring treatment before safe discharge. Solid waste comprises combustible materials like paper and non-combustible components from the reactor core, necessitating appropriate packaging and sometimes volume reduction [*World Nuclear Association,2021*]. Radioactive waste is further classified into four classes based on radioactivity levels and potential hazards. Very Low-Level Waste (VLLW) contains minimal risk and can be disposed of within domestic waste, while Low-Level Waste (LLW) includes materials with low radioactivity levels, safely disposed of in shallow landfills. Intermediate-Level Waste (ILW) comprises materials with higher radioactivity levels and demands more advanced treatment and disposal methods. High-Level Waste (HLW) is the most hazardous, requiring sophisticated treatment, conditioning, and disposal due to its high radioactivity levels, including used nuclear fuel and materials from the reactor core [*World Nuclear Association,2022b*]. Proper management and understanding of these waste types and classifications are essential to ensure safe handling and protect the environment and human health.

This research investigated the optimal and safest site for a high-level waste deep geological disposal facility. To facilitate this process, we propose crucial factors and data that should be considered. These factors are not exhaustive guidelines, but they serve as a starting point to be integrated with regulations, socioeconomic aspects, and country-specific characteristics. Key factors include the geological setting, which should inhibit radionuclide movement and have sufficient depth and dimensions; hydrology, requiring data on groundwater flow and restrictions; geochemistry, with a focus on minimizing radionuclide release; consideration of future natural changes and potential geodynamic events; suitable land usage and environmental protection measures; social impacts and potential human activities; and lastly, the transportation of waste with minimized radiation exposure [*IAEA Safety Series: Siting of Geological Disposal Facilities, 1994*]. Additionally, this paper delves into the deep geological repository concept, discussing the underground development process, drill and blast excavation methods, rock support requirements, and phases of construction and operation. Overall, our research aims to determine an optimal location for the repository while prioritizing safety and environmental protection.

II. Literature Review

Over the past 50 years, scientists have developed various methods and tools to contain, store, and dispose of radioactive waste. Nuclear Engineering science has also focused on harnessing nuclear energy's benefits while safeguarding the environment and future generations. Saudi Arabia is actively working on its nuclear program to produce clean energy, which includes Radioactive Waste Management for all classifications of radioactive waste. Although there is currently no clear plan for High-Level Radioactive Waste (HLW) management in the country, it is expected that deep geological disposal will be considered as one of the options beyond 2030. Although this approach has been adopted in many countries worldwide, it is implemented in countries like France (Cigeo Project), the United States (Yucca Mountain), China (the Gobi Desert), and Finland (Onkalo).

The Cigeo Project in France began in 1991 to address radioactive waste concerns. After extensive research and consideration, the French government chose deep geological disposal as the only permanent solution for HLW. Andra, the French national radioactive waste management agency, was assigned to design the disposal facility, located in the Meuse and Haute-Marne department. The Underground Research Laboratory, constructed in 2000 at a depth of 490 meters, confirmed the feasibility of deep geological disposal in the Callovo-Oxfordian argillite stratum [*Andra Documentations: The Cigeo Project,2020*]. The chosen geological stratum's stable and permeable properties, along with its 145-meter thickness at depths between 400 and 600 meters, make it an ideal location for the disposal site. Analyzing the Callovo-Oxfordian argillites revealed its composition, primarily consisting of clay minerals, calcite, and quartz, with pore water representing 8% of its weight [*Lavastre, V. et al, 2002*].

China has identified Beishan, a strategically critical geological spot in the Gobi Desert, as a potential location for a deep geological repository for high-level waste disposal. The area is dominated by granite plutons and is considered the most stable region within the active fault zone due to the buffer impact of the Qilian Mountains [*Wang, Z. et al, 2022*]. To study the area, China has established an underground research laboratory (URL) with specific siting criteria, including geological, hydrogeological, and engineering considerations. After a thorough selection process, the Xinchang site in the Beishan region was chosen as China's first URL site [*Wang, J. et al., 2018*].

In Finland, the Olkiluoto Island was selected as the location for the final disposal of nuclear waste. The bedrock has been extensively studied to ensure its suitability for long-term disposal, and ONKALO, a combination of shafts and an access tunnel, was constructed to reach the necessary depth for disposal. The bedrock's stability and isolation properties provide a secure environment for the engineered release barriers to remain operational for an extended period [*Finnish Energy Industries,2007*].

Yucca Mountain, located in Nevada, United States, was chosen by the U.S. Department of Energy (DOE) in 1987 as the proposed site for the nation's first permanent geologic repository for high-level radioactive waste and spent nuclear fuel. This repository, situated around 100 miles northwest of Las Vegas, is in a remote desert region and is composed of volcanic tuff, a compacted rock formed from volcanic ash. The main objective is to store high-level radioactive waste in underground tunnels and chambers within Yucca Mountain. The waste, transported by rail or truck, will be placed in specially designed containers called canisters and then stored at depths ranging from 1,000 to 2,000 feet (305 to 610 meters). To ensure safety, the design of the repository includes several barriers, such as the natural geology of Yucca Mountain, engineered barriers like steel canisters and concrete structures, and comprehensive monitoring systems. These measures aim to prevent radioactive material from escaping into the environment and address potential concerns about public health and the environment. The waste forms to be stored in the repository consist of stable solid materials, falling into two categories: spent nuclear fuel and high-level waste. The total inventory of these materials in the U.S. may eventually exceed 100,000 metric tons of heavy metals and is currently stored in various locations across 39 states. Despite the efforts made to ensure the safety of the site, the Yucca

Mountain project has been met with controversy due to concerns surrounding its safety and environmental impact [*U.S. DOE Yucca Mountain Science and Engineering Report,2002*].

A study that was done in 2014 [*Al-Othmany, D., 2014*] to investigate the feasibility of a high-level radioactive waste storage facility in the kingdom suggested two in or near the empty quarter. The choice was made due to the nature of the area in regard to rain rareness, seismic activities, and freeness of formation or surface waters. These locations were chosen as a preliminary assessment and recommendation of what seems to be the most practicable places for long-term considerations of storage or disposal of HLW.

III. Methodology

The study primarily used Geographic Information System (GIS) integrated with natural geological data about the structure of the kingdom to analyze these geographical data. The GIS is a free, open-source program used for writing, editing, printing, and analyzing geographical data. It supports raster, vector, and mesh layers, with vector data stored as points, lines, or polygons. GIS offers various features, including adding Google Satellite Maps, importing online data, fetching earthquake data, and measuring areas [*QGIS Org., 2023*]. The method for creating maps involves importing a Google satellite map using the HCMGIS base-map plugin and drawing the Kingdom's political borders on top. Additionally, earthquake data from 1900 to 2023 is collected using the Q-quake plugin. Public domain data is collected for waterways, buildings, land use, and points.

The geology of the Kingdom of Saudi Arabia is characterized by a tropical or subtropical desert with three zones: highlands, a steep zone along the Red Sea coast, and a desert elsewhere. The study focuses on two main regions: the Arabian Shield and the Arabian Shelf. The Arabian Shield, covering 650,000 square kilometers, is a Precambrian rock formation rich in minerals [*Nehlig, P. et al, 1999*]. The Arabian Shelf, characterized by low-dipping, relatively undisturbed sedimentary beds, provides an attractive area for the research objective. The site characterization process identifies Al-Nufud desert in the north as a potential site for a deep geological repository due to its limited waterways and distance from populated areas. The geology indicates low seismic activity, making it suitable for the repository project. However, Al-Nufud Desert is excluded from further consideration due to its proximity to important natural reserves, historical significance, the presence of major train rails, increasing population, and potential future development plans in the area. On the other hand, the Empty Quarter (Al Rub' Al Khali) Desert in the south,

with its vast area, limited waterways and rainfall, uninhabited nature, seismic stability, and suitable geological composition, emerges as a promising location for a deep geological repository. To fully assess its potential, detailed geological studies, involving borehole drilling and rock sample analysis, are necessary.

IV. Results and Discussion

Based on the studies conducted using the geographic information system and geological data, both the Al-Nufud desert and the Empty Quarter were initially considered as potential locations for a deep geological repository.

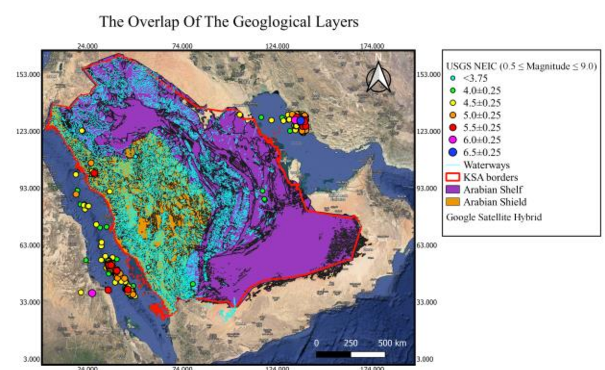

Figure 1 final overlapped layer map

However, further research, taking into account social, economic, industrial, and developmental factors, led to the exclusion of Al-Nufud desert. This decision was influenced by its proximity to planned future projects and important historical sites. On the other hand, the Empty Quarter emerged as a more suitable choice due to several key factors. With an extensive area of 650,000 square kilometers, it offers ample space, comparable to the size of France which is 549,087 square kilometers [*World Data, 2019*] with approximately 100 square kilometers to spare, allowing for projects to be established with significant distances between them. The absence of clear water routes in the desert's deep structure is crucial for a nuclear facility location, as it prevents radioactive materials from traveling long distances in the event of a leakage. Moreover, the area's historical earthquake data reveals a stable and safe environment, ideal for a deep geological repository [*United States Geological Survey, 1900-2023*]. The low- to non-annual rainfall percentage further ensures minimal risks related to radioactive materials traveling through water routes. The geological structure of the Empty Quarter consists of Mesozoic sediment rocks formed millions of years ago [*R. W. POWERS. et al, 1966*], showing similarities to other successful projects like the French repository Cigeo, except that in Cigeo, the geological stratum is made of

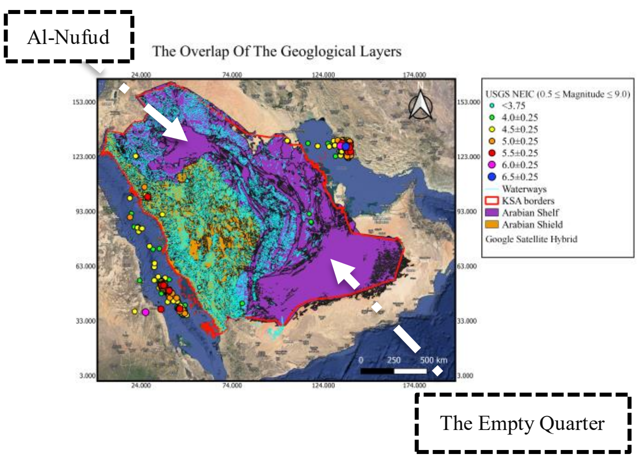

Figure 2 Areas of the study

argillaceous sedimentary stratum that is 160 million years Callovo-Oxfordian argillite. Furthermore, the empty quarter's stratum is similar to the current undergoing project in Canada, which lies on both crystalline and sedimentary rocks, which are assumed to contain high-quality rock [*NWMO Deep Geological Repository Conceptual Design Report Crystalline / Sedimentary Rock, 2021*]. Leveraging the experience and knowledge from these previous projects enhances the chances of successful implementation, facilitating the project's complexity and ultimately leading to its successful establishment. Deep geological repositories are intricate endeavours that require significant time, learning, analyses, data, experiments, and human resources. Utilizing existing experiences can provide valuable insights, predict potential challenges, and guide engineers and scientists toward achieving the ultimate goal.

V. Conclusions

This research focused on nuclear waste management and the search for a suitable location to establish the first National Deep Geological Repository for Saudi Arabia's nuclear power program. The study explored the geological structure, seismic history, rock types, waterways, mineral distribution, population, and potential developmental projects within the Kingdom. Based on the analysis, two possible locations emerged: Al-Nufud and the Empty Quarter Deserts. While Al-Nufud initially seemed promising, it was eventually excluded due to future developmental concerns. The Empty Quarter Desert met all the criteria and was identified as the proposed suitable site for the repository. This project aims to provide valuable guidance to decision-makers and contribute to the scientific community and the Saudi Arabian nuclear industry. The study presented detailed results and justifications for selecting the location. However, further in-situ studies and investigations are required to make a final decision on the suitability of the Empty Quarter as the repository location.

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