Use of Underground Space and Technology in Nuclear Fuel Cycle

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Abstract

There are several applications of the underground space in the field of nuclear energy and associated sciences. Two such applications, of particular significance for future large scale deployment of nuclear energy, pertain to the use of such space for geological disposal of the long term nuclear waste and underground siting of nuclear reactors. Studies on the elusive particle neutrino also call for underground Neutrino Observatory. This paper discusses the aforementioned three areas for the use of underground space.

Introduction

The drive towards a sustainable future means investigating new ways to allow the requirements of economic growth, whilst preserving our natural environment. Increasingly, underground space is seen as playing a more significant role in the cities of the future. There are many application areas where underground space is already being utilised. These applications include mining, storage and distribution pipe lines for water and petroleum, routing of electrical, communication and control cables, metro railways, railway stations, roads, navigation tunnel, subway, parking, sewage and flood control systems, water transfer tunnels etc. Besides these conventional uses, there are many application areas related to energy production and storage, where underground space offers many advantages. Some of these applications are: underground gas storage, compressed air energy storage, geothermal energy production, carbon dioxide sequestration, and underground hydrogen gas storage.

Use of underground space is common throughout the world in both the front as well as the back-end of the nuclear fuel cycle. This includes mining of nuclear materials and interim storage of nuclear waste. Permanent underground repositories for storage as well as disposal of nuclear waste offer a long-term solution to the nuclear waste issue. Underground reactor concepts are also attracting attention due to some unique features. Another important area pertinent to nuclear science, where underground space is essential, relates to cosmic ray experiments in underground laboratories setup in mines or at times specifically built facilities.

Use of Underground Space for Geological Disposal of Nuclear Waste

Long-term sustainability of nuclear power generation depends, to a large extent, on acceptable solution to the radioactive waste management. The concerns mainly emanate from the long half-lives, some of the radioactive nuclides constituting part of such waste. Currently, a lot of R&D work is in progress world-wide to reduce radio-toxicity of such waste by actinide separation and re-use of other heat emitting radioisotopes in medicine and industry. There are also efforts to burn long-lived radio nuclides in specifically designed advanced reactors and accelerator driven systems. Despite the potential success of such efforts in the future, the relatively small volume of the left-over waste with long-lived residual radioactivity will need its safe disposal.

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Two specific types of underground disposal of radioactive waste are being practiced now-a-days world-wide. The wastes with low and intermediate level of radioactivity with very high volumes and carrying only about 1% of the total radioactivity handled in the nuclear fuel cycle are invariably disposed in specifically designed engineered structures, both above-ground as well as at shallow depth in underground space within the earth. As most of the radioisotopes in these wastes are short-lived with lower radioactivity levels, shallow disposal provides isolation for a few hundreds of years. In India, such wastes, after their volume reduction and immobilisation in suitable solid matrix, are disposed in Reinforced Concrete Trenches, Earth Trenches and Tile holes located in the first 5-10 m below the surface. Integrity of these structures is continuously evaluated and necessary design modifications are introduced to enhance their performance and service life.

The other scheme of the disposal involving the long-lived and heat emitting nuclear waste, popularly known as high level waste, that arise from the reprocessing of the spent fuel and in some countries the spent fuel itself, poses significant technological challenges. Such waste amounts to almost 99% of the total radioactivity handled in the nuclear fuel cycle. The complexity associated with such disposal emanates mainly from the very long half-lives of the radioisotopes of a few actinides, coupled with heat emitting nature of a few fission products like radioisotopes of Caesium and Strontium. Hence, permanent disposal of such waste requires their isolation from the environment, over periods running into tens of thousands of years. With the potential for large scale global growth of nuclear power, the issue needs to be addressed in a timely manner. Possibility of disposal of such waste in deep underground space has attracted the attention of waste managers, right from the beginning of the expansion of nuclear power generation world-wide. A number of solutions, to achieve isolation for such extended duration of time and provide long-term safety to human and biota, have been proposed in last six decades. The most promising and feasible option is the disposal of such waste into specifically designed and constructed facilities at appropriate depth in suitable rock types beneath the surface of the earth. Such facilities are popularly known as Deep Geological Repositories (DGR). Some of the important components and considerations of DGR are multilayer safety systems, site selection and characterisation, host rock considerations, design and construction to ensure long term passive safety, demonstration of safety and public acceptance.

Major technological issues in the use of underground space for waste disposal are related to site selection, its characterisation, design, construction, waste handling, transport, sealing and back-filling of weak zones and final closure of the facility. International experience in site selection reveals that no site chosen for hosting DGR, in its natural condition, can qualify as an ideal site that can provide desired level of safety over extended periods of time. As is only to be expected, a number of natural deficiencies like presence of pockets of weak rocks in otherwise good rock mass, presence of weak zones like fractures, faults, etc. in some part of the site, adverse groundwater occurrence and chemistry, etc. do occur in parts of any candidate site. These shortcomings are addressed by improving the design of the underground structures and excavation technologies, use of suitable backfill and seal material, etc. to mitigate deficiencies imposed by these site characteristics. The excavation, operation and closure methodology needed for DGR development are significantly different from the ones used in normal mines, as all these operations need to be carried out in very controlled manner to avoid any additional damage to the host rock. The DGR in its simplest form will comprise access shafts for waste, man and machine transport, ventilation shaft, a network of disposal tunnels of few kilometers length and few thousands disposal pits.

The radioactive waste immobilised in a suitable matrix and contained in steel overpacks can be disposed in these disposal pits. Studies have demonstrated minimum requirement of about four square kilometer subsurface span of such facilities in the case of granite host rocks. Some of the key issues associated call for adaptation of innovative technology for construction of access shaft/ drive/decline, transportation tunnels, and disposal pits. Besides, these facilities also warrant specific measures to minimise stability problems due to geological and thermal stresses, and to maintain lower hydraulic conductivity of the host rock in accordance with the site specific rock mass characteristics to achieve self-supporting underground structures, without any appreciable support systems. The sealing of fractures in rocks of such repositories, to avoid ingress of groundwater, necessitates development of very high durability, geochemically compatible seals and pressure injection technology. The regulatory requirement of such a facility requires assessment of the impact of depth on the possible damage to the underground structure when struck by earthquakes of varying intensity and magnitude. Studies conducted have shown that the probability of seismic induced damage is very low.

In India, a conceptual design and layout of deep geological repository with a capacity to host 10000 waste overpacks have been worked out, based on available geological, hydro geological and rock mechanical data of a few granitic rocks. The facility, at 500 m depth, includes one main shaft (6m diameter) for accessibility, and another ventilation shaft of 4m diameter, with two orthogonal transportation tunnels of 2 km length each. These provide four panel disposal areas each with 800m length and 110m width. In each of these panels, a total of 63 disposal tunnels (110m) with capacity of holding about 40 waste overpacks each are aligned at right angle to each transportation tunnel and parallel to the direction of principal in situ stresses. The DGR, thus, has a total of 242 disposal tunnels. The disposal tunnel of 4m diameter and 4m height has been found stable under the combined impact of geological and thermal stresses. Combined thermal and mechanical stresses around a single disposal pit, with waste overpack, have been analysed using mathematical modeling and the pit has been found stable over a period of 1000 year without any significant rock damage.

Indian Underground Research Laboratory (URL)

Underground Research Laboratory serves as test bed for developing methodology and technology required for geological disposal of waste. India operated an Underground Research Laboratory in an abandoned section of Kolar gold mine at a depth of about one kilometer during 1980 to 1990. During this period, an experiment involving development of methodology and technology for excavation of large diameter disposal pit, without causing much damage to the host rock, emplacement of waste overpack, installations of monitoring devices and development of computer modeling codes for prediction of heat profiles across the waste overpack were carried out. Currently, efforts are on to set up an Underground Research Laboratory in granite to develop methodology and technology needed for development of final DGR for waste disposal.

Underground Reactor Concept

The underground reactor concept has the nuclear reactor installed in an underground pit with low exterior profile of the reactor building. Underground reactors have their containments constructed in mined cavities or pits that are then backfilled with thick layers of rock and soil. Multiple research reactors, several military reactors, and one power reactor have been built underground in the 60s and the 70s. Today, there are added incentives that make underground siting a preferred option. There are many advantages, such as inherent protection provided against postulated missile and aircraft impact, blast effects due to chemical explosions, reactor core meltdown and tornadoes, and benefits of structural and biological integrity. Other advantages are potential for urban siting, ecological considerations, reduced effects on the landscape, increased number of acceptable units and power capability from a single location, additional confinement of radioactive materials, additional protection of public from direct radiation exposure, small land usage, and reduction of decommissioning problems. Conventional aboveground containments are designed to resist assaults and accidents because of the strength of their construction materials and the effectiveness of their safety features that are engineered to reduce loads. However, underground containments can provide even more resistance because of the inertia of the mass of materials over the reactor. The structural response to seismic impact advantages has been observed for buried plants, because some attenuation effects regarding the depth arise due to seismic induced motions. Experimental data on earthquake motion reviewed in the USA and Japan indicate reduction factors of the order of four and five, under these conditions.

Such concepts are especially attractive for hydrogen production by nuclear reactors. Since hydrogen is a combustible gas with explosion possibility, safety codes recommend a safe distance between the hydrogen production plant/storage system and the nuclear power plant along with a sturdy blast wall between the two plants to offer protection to the nuclear plant. It becomes challenging to transport process heat from the nuclear reactor to the hydrogen production plant located over a large distance without losses and temperature drop. Underground nuclear reactor with hydrogen production plant on the surface provides an ideal alternative and is an efficient option.

However, there are many challenges for underground siting of the nuclear reactors, viz. limitation of the height of the structure (rock caverns), ground water problems - particularly during construction, longer construction periods, less flexibility within the plant for later changes and technical innovations, effects of soil and water pressure, adequacy of containment for subsequent use of storing radioactive materials, etc. The siting criteria and structural selection factors for underground nuclear power plants (including surface components) take into account the guidelines for seismic design of nuclear power plants. The guidelines are based on geotechnical data, seismic loading, configuration and embedment, typical sizes and shapes of underground openings, structure types, static and dynamic analysis, laboratory and field measurements, faults, possible path of leakage of radioactivity, ground water control, environmental factors, etc.

Siting criteria for an underground reactor needs additional considerations. Some of these are related to geotechnical data such as rock type, their strength, planes of weakness, groundwater considerations, groundwater pressures, and potential seismic wave loading. The placing of the containment underground introduces a provision for elastic restraint all round the structure, resulting in reduction of pressures normally encountered in surface structures.

In underground construction, vital parts of the plant are completely contained by natural materials of sufficient thickness. The advantages are essentially the same as those for underground rock locations; however, the structure supports the fill, in contrast to locations in rock or hard ground, where the cavity walls and roof are designed to be substantially self-supporting by reinforcement with rock bolts. Roof and wall liners are designed to carry the soil overburden. The different types of structures, which have been analysed, include cut-and-cover structure, unlined cavity, lined cavity, and lined cavity with annular filling.

Use of Underground Space for Hosting Neutrino Laboratory

Underground spaces with sufficient overburden of rock mass serve as ideal places offering opportunity to detect and study neutrino. The solar neutrino experiments of Davis and collaborators in USA, the gigantic Super-Kamiokande detector in Japan, the heavy-water detector at the Sudbury Neutrino Observatory in Canada, and a few other laboratories, together, have contributed in a very fundamental way to our knowledge of neutrino properties and interactions. India has also made significant contribution in this field. In fact, cosmic ray produced neutrinos were ?rst detected in the deep mines of Kolar Gold Fields (KGF) in 1965. Currently, it is planned to revive underground neutrino experiments in India. A multi-institutional National Neutrino Collaboration has been formed with the objective of building an India-based Neutrino Observatory (INO). A few geological domains have been shortlisted meeting basic site selection criteria to host underground neutrino laboratory. These criteria give importance to long-term availability of the site, construction costs and operating costs.

Summary

The underground space and technology finds prominent application in many activities of the nuclear fuel cycle in general and in permanent geological disposal of radioactive waste in particular. Decades of work for the development of relevant methodologies and technologies in Underground Research Laboratories world over have indicated that geological isolation of radioactive waste is safe, environmentally sound, and is a permanent solution. The outcome of these activities have amply demonstrated the feasibility of disposing such waste into specifically designed and constructed Deep Geological Repositories at appropriate depth in suitable rock types beneath the surface of the earth. The capability of such rock types in providing isolation and confinement to waste stands well demonstrated since the existence of rock types at depth have remained virtually unaltered over millions of years. On the other hand, underground nuclear reactors could possibly be a means to produce electricity and hydrogen, to supply to the grid, and provide further enhanced margins of security, safety and proliferation resistance. This opens a new approach and may lead to higher levels of public acceptance, perhaps lower capital and operating costs relative to equivalent surface-sited nuclear power plants.