RADIOACTIVE WASTE MATERIALS AND DISPOSAL APPROACH

Supported by tetfund

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Received: May 30, 2020 **Accepted:** September 05, 2020

Abstract: This paper is a review on radioactive waste materials and disposal approach. Radioactive wastes are produced, year in year out from nuclear plants, industries, medical and military facilities. These wastes have been classified based on their half-lives, activity and/or origin by nuclear regulatory bodies. Some have over the years been stored in a dry or wet medium prior to when an appropriate means of disposal will be made available, in such a way that both man and environment are not affected negatively. However, ways to which they can be disposed have emerged and assigned to different types of radioactive wastes. These wastes emanate from various activities, sources, means and/or places. Radioactive wastes that pose highly dangerous to man and environment if not properly curtailed have been designated to be disposed in Repositories built several kilometers into the subsurface. These facilities undergo several analytical stages and processes before it is approved for construction, as certain frameworks for radioactive waste managements need to be assessed critically. Countries without these disposal means have commenced construction while some have solicited to aid countries that cannot construct such facilities in disposing their high level radioactive wastes or spent nuclear fuels.

Keywords: Radioactive wastes, radioactivity, spent nuclear fuel, disposal, regulatory bodies

Introduction

Radioactive wastes are those hazardous materials that contain radioactivity or radioactive substances or elements (isotopes) in them. They are either irradiated materials that are no longer in use, spent fuels (nuclear wastes) or by-products of atomic fission from reactors or nuclear fuels or power generations (Carter, 1987), having varying physical, chemical and radiological characteristics. Radioactive waste is classified as low level waste, intermediate level waste, high-level waste and transuranic waste according to the amount and types of radioactivity in them (Barney, 1992). They are by-products or substances no longer useful and are contaminated by or contain long-lived, short-lived and non-radioactive nuclides (Jablonski, 2001).

Radioactive wastes are defined for legal and regulatory purposes however as “wastes that contain/contaminated with radionuclides at concentrations or activities greater than clearance level as established by a regulatory body” (IAEA, 2003). These wastes can be generated from nuclear power and research plants, military defense operations, agricultural researches, medical and healthcare laboratories, industries producing coal, oil and gas, etc. (ANDRA, 2016). The radioactivity of these wastes decrease over time, but there are those that have a decay half-life of over millions of years which would take a very long period of time before the completely decay. As quoted by James D. Werner (May, 1996): “These materials we are dealing with cannot go away entirely until they decay. You can only containerize them, solidify them, immobilize them and move (change location by anthropogenic means), but you cannot make them go away” (Mederal, 2011). It has been a challenging task for centuries running by as to how to safely discard these contaminated materials and spent fuels in a manner that would create a safe and secure habitable environment for all. A radioactive waste is termed “spent” ifa source is no longer needed (e.g. replaced by a different technique) or it becomes unfit for the intended application (e.g. activity becomes too weak, malfunctioning or obsolete equipment, damaged or leaking source) it is considered spent. A spent radioactive source (SRS) may still be highly radioactive and potentially dangerous to human health and the environment (Kademani *et al*., 2013).

Types of Radioactive Wastes

There are different types of radioactive wastes that have been classified based on their half-lives, activity and/or origin of the wastes by the IAEA and the US National Nuclear Security Administration classification systems (Fig. 1).

Exempted waste (EW): These are wastes that have been classified to have met with the criteria for clearance and are been excluded from regulatory control for radiation protection purposes (IAEA, 2009, 2018).

Very short lived waste (VSLW): These waste are very short lived, that is, they have a very short half-life of just few years. These types of wastes are however been cleared for regulatory control, which is according to the arrangements made and approved by regulatory bodies for ‘uncontrolled’ disposal, utilization or discharge (IAEA, 2009).

Very low-level waste (VLLW): These forms of radioactive wastes are not harmful to people and to the environment. They do not necessarily meet the criteria of **EW**, which doesn’t need a high level of containment and isolation. It is therefore suitable for disposal in near surface landfill type facilities where there is a limited regulatory control (IAEA, 2018). Examples of these materials are bricks, cement, plaster, paint, ceramics, metals, valves, piping, concrete, etc. These waste materials are products of rehabilitation or dismantling operations on nuclear industrial sites. However, it is important to mention that other industries (such as steel, food, chemical, cosmetics, etc.) also produce VLLW. These industries that indulge in food processing, steel and chemicals production use certain minerals in their manufacturing processes which contain certain level of natural radioactivity. This kind of waste is disposed with domestic refuse. Some countries, such as France, are currently developing facilities to store VLLW in special disposal facilities (Hore-Lacy, 2010; WNA, 2017).

Low-level waste (LLW): These forms of wastes are often generated from nuclear fuel cycle, form industries and medical centres or hospitals. They have a radioactive content of about 4 Giga Becquerel/tonne of alpha activity or 12 Giga Becquerel/tonne of beta activity. They contain mostly short-lived radioactivity and can easily be disposed by shallow burial or in surface facilities. However, they are to be handled with care, given special treatment before disposal and should be shielded when transporting (mostly those that may have high-activity, otherwise LLW does not require shielding) (WNA, 2018). Ways in which they can be treated are through: mechanical volume reduction, dewatering, solidification, thermal transformation, sorting, segregation decontamination and stabilization. LLW can compacted, reduced to a given size or amount before giving it off into the incinerator (i.e.

after several steps have been taken to reduce the radioactivity level of the LLW to the barest minimum or ALARA (As Low As Reasonably Achievable) before incinerating. Examples of LLW are cloths, rags, tools, gloves, mops, towels, paper, aprons, etc. (WNA, 2018).

Intermediate-level waste (ILW): These forms of wastes have radioactivity level (>4%) higher than the low level waste materials. They are shielded in most instances, solidified in bitumen or concrete before final disposal. Materials classified as ILW with higher activity level than LLW are: contaminated materials which are by-products of reactor decommissioning, resins, metals, fuel cladding and chemical sludge (WNA, 2017, 2018). As a result of this, they require a greater degree of containment and isolation than that provided by near surface disposal as is in the case of the former. However, ILW needs limited provision for heat degeneracy during its storage and disposal (IAEA, 2018).

High-level wastes (HLW): A nuclear fuel rod that has served as a driving fuel for a reactor is known as a spent fuel, and is tagged a high level waste (Rogner, 2010). In other words, they are products of nuclear reactors which contain radioactive elements such as uranium and in some cases, plutonium. They are highly radioactive, emit high radiation and heat (>2 kW/m^3), and about more than 34,000 metric cubes (12,000 metric tonnes) are produced annually from countries that have nuclear power/ reactor plants (WNA, 2017, 2018). During storage and transporting, they are to be cooled and shielded (WNA, 2018).There are two distinct types of HLW: used fuel that has been designated as waste (i.e. HLW generated directly from reactors as spent fuel), and separated wastes from reprocessing of used fuel (i.e. HLW generated indirectly after reprocessing of used fuel) (WNA, 2018). Other forms of HLW are vitrified glass, calcine, sludge, and other forms in which the liquid HLW can be converted to before storage or disposal (Kademani *et al*., 2013). High-level wastes are mostly disposed by burial, in boreholes or in isolation pilot plants that have deep geologic repositories (WNA, 2015). They are enclosed in casings or casks made of glass, ceramic or materials made of nanostructures which allows the wastes to emit radiation, shields the radiation from escaping and are themselves not affected by the radiation (Clark and Ewing, 2006). It has been quite challenging and tasking to execute deep geologic repository mode of waste disposals, and it somewhat generates constrain in the global expansion of the nuclear industrial field (Findlay, 2010). HLW can be retrieved, reprocessed and recycled/reused to reduce the level of radioactivity it contains before final disposal (Biello, 2011). Under this class is the "**Transuranic Wastes (TRUW)".**

They contain radioactive elements with atomic number greater than uranium (e.g. plutonium and neptunium) are classified as transuranic wastes. TRUW are composed of radionuclides that emit alpha particles and have half-lives greater than 20 years. They are generated from nuclear reactors as a form of spent fuel and also generated from facilities that produce weapons. They emit very high radiation and require outmost shielding during disposal or transporting (Kademani *et al*., 2013). They are categorized into two types; the contact-handled and remotely-handled TRUW. The former is lower than 200 mSv/h and the latter is equal to or greater than 200 mSv/h. the remotely-handled TRUW is more radioactive and can be classified as a high-level waste, unlike the contact-handled TRUW. In the United States of America, these wastes are disposed in a Waste Isolation Pilot Plant (WIPP) situated in New Mexico (DOE/CBFO, 2003). It was initiated as the first mode at which transuranic wastes were disposed in an underground repository in the 1980s and commenced operation in 1999 (DOE/CBFO, 2003).

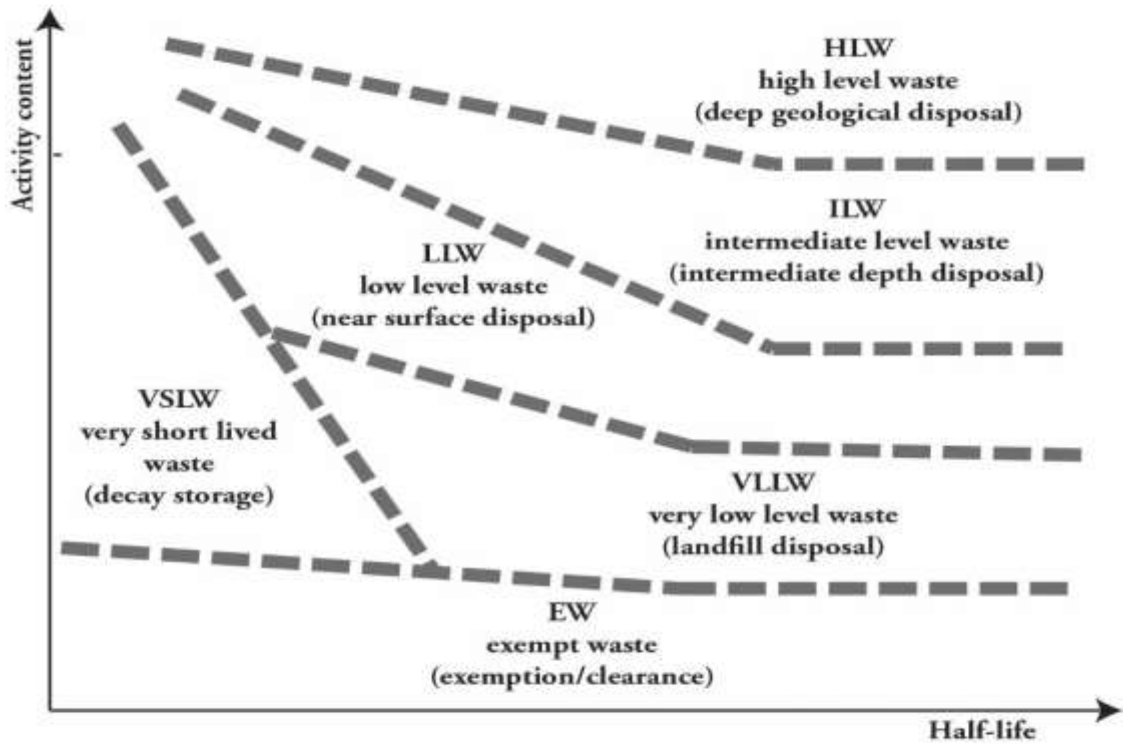

Fig 1: An illustration of radioactive waste classification scheme by the IAEA (2009)

All the above mentioned can be categorized based on either the form of the waste (solid or liquid), based on the level of radioactivity (high or low), based on the types of elements or materials it's made up of (uranic or transuranic) and based on the origin of the wastes (from medical centres, reactor facilities, agricultural, mines, etc.) (Klien, 1991). It is however important that harmful radiations emitted from these wastes are contained to avoid contaminations and the materials are disposed of properly so as to avoid hazardous effects to people, animals, crops and the environment at large.

Major sources of radioactive wastes

Radioactive wastes can be sourced from several places, be it from the field, medical and research laboratories, industries or from military/defense bases. They range from very low level wastes to high level wastes. However, means by which these wastes are stored and/or disposed are equally suggested to prevent contaminations or radioactive exposures to humans and environment. Some of these sources with examples are below:

From nuclear power, research and other power reactors: There are about 70 nuclear power research and other reactors in the world. Some are active where as others have been dismantled due to their shut down. The dismantled parts of the reactor, used materials that have been contaminated with radioisotopes and spent fuels are then taken and handled as radioactive wastes which need to be stored and eventually disposed of properly to avoid hazards. For the used fuel otherwise referred to as spent fuel, are highly radioactive (high level wastes) as they contain uranium, plutonium and other heavy elements, thus, they are stored for several years in a fuel pool. When safer to handle, it is moved to an interim storage facility. However, spent fuels can be retrieved, reprocessed and reused. The other materials and parts of the reactor that may have been contaminated by radioactive substances are classified as very low, low or intermediate level wastes, which still need to be contained, packaged and stored before proper disposal methods are suggested for them (IAEA, 2018).

From nuclear fuel cycle: In a nuclear fuel cycle facility, radioactive wastes are generated in all the steps of material production, extraction or fabrication. This includes:

a. Uranium mining and milling
b. Conversion of uranium oxide to uranium hexafluoride and back.
c. Enrichment
d. Fuel fabrication
e. Reactor operation
f. Spent fuel storage
g. Reprocessing and manufacturing of new fuel containing uranium or a uranium/plutonium mixed oxide (MOX) (IAEA, 2018).

Most of the wastes produced here fall between very low to intermediate level wastes, for instance wastes from reprocessing and manufacturing cycle (such as fission products, minor actinides, metallic structure of the fuel). However, at the end of the nuclear fuel cycle’s life, every part of the facility and materials used are termed decommissioning wastes (IAEA, 2018).

From uranium mining and milling: during the mining and milling of uranium in the field, some wastes are formed, especially the rocks from which the uranium is mined from and the overburden rocks, but fall under very low level wastes. The mill tailings are the residues after uranium has been extracted from the material bearing the ore. However, these wastes can be disposed directly into the environment which will have little to no effect to both man and environment, but it is better if kept away to minimize radiological and non-radiological impact to environment and man. Radioactive residues are also produced in oil and gas industries as scales and sludge; in the mining of thorium and rare earth elements and during water treatment processes (IAEA, 2018). These are wastes produced from the processes that involve the extraction and processing of uranium ore into fuels for nuclear or research reactors. Some are regarded as not very radioactive but may however contain traces of radium, radon, thorium, and uranium. They could also contain chemically hazardous elements such as lead and arsenic (USNRC, 2017). Disposing small amounts of these wastes into the environment may not pose any threat but disposal of large quantities of wastes may have an environmental impact as a result of the long half-lives and the ready availability of the toxic radionuclides Ra-226 and Rn-222 (Thomas, 1981). Also in this category are uranium mining waste residues from extractive industries and contaminated soils which are typically disposed of in situ because they can be impractical to transport elsewhere. However, the contaminated materials are placed in stable mounds with an appropriate cover system that provides isolation from the immediate environment (IAEA, 2018).

From research, medical and industrial use: Radioactive wastes emerge from materials that have been exposed to forms of radiation or contaminated by radioisotopes. Radioactive sources used in these facilities which are no longer in use or abandoned are classified as wastes. Radioactive tracers (form of radioactive source) that are no longer in use are treated as wastes. They are used in medical field for radiotherapy and irradiation of blood, whilst in the industrial and research fields they are used for calibration of detectors or measuring equipment, testing materials, irradiation, detection and sterilization of products. The wastes generated from here are either low level or intermediate level wastes depending on the degree of contamination (IAEA, 2018).

From military or defense programmes: Radioactive wastes mostly produced from such programmes are rarely known or reported, as the wastes are mostly from the production of weapons or war fares (IAEA, 2018).

1. **Legacy wastes:** Legacy wastes are those voluminous radioactive wastes generated from nuclear power plants, as nuclear technology and power production programs/generation increased in countries that have these facilities. They are a liability to some countries (e.g. U.K, U.S.A, Russia and France) sometimes difficult to manage and about 30% of it is attributed to military programs (WNA, 2018).
2. **Decommissioning nuclear plants:** These are simply radioactive wastes from the cleaning/clearing up or shutting down of a nuclear plant. These wastes have very low to low radioactivity compared to those wastes produced from reactor operations. Their level of radioactivity tends to diminish over time (IAEA, 2004). However some tend to be high, especially those materials (metallic components) that was in direct contact with the reactor during neutron irradiating. These scraps are either recycled or buried (WNA, 2018).
3. **Other sources:** These include materials that have been contaminated by radioactive sources in the fields, buildings, dismantled facilities, etc.

Types of radioactive wastes disposal methods

Radioactive wastes need to be kept away from the general public and the environment at large. They are hazardous to an extent depending on the level of radioactivity the wastes contains. Some modes of radioactive waste disposals adopted by countries that generate them are listed and explained below. However, there are other forms of disposals that are yet to be implemented, while some have been rejected by government policies and/or the masses of the country (ies). Whatever the disposal method to be adopted, has to be in agreement with the government and regulatory bodies, be viable and state of the art (standard) (Rao, 2001; Jack and Robertson, 2008) (Fig. 2).

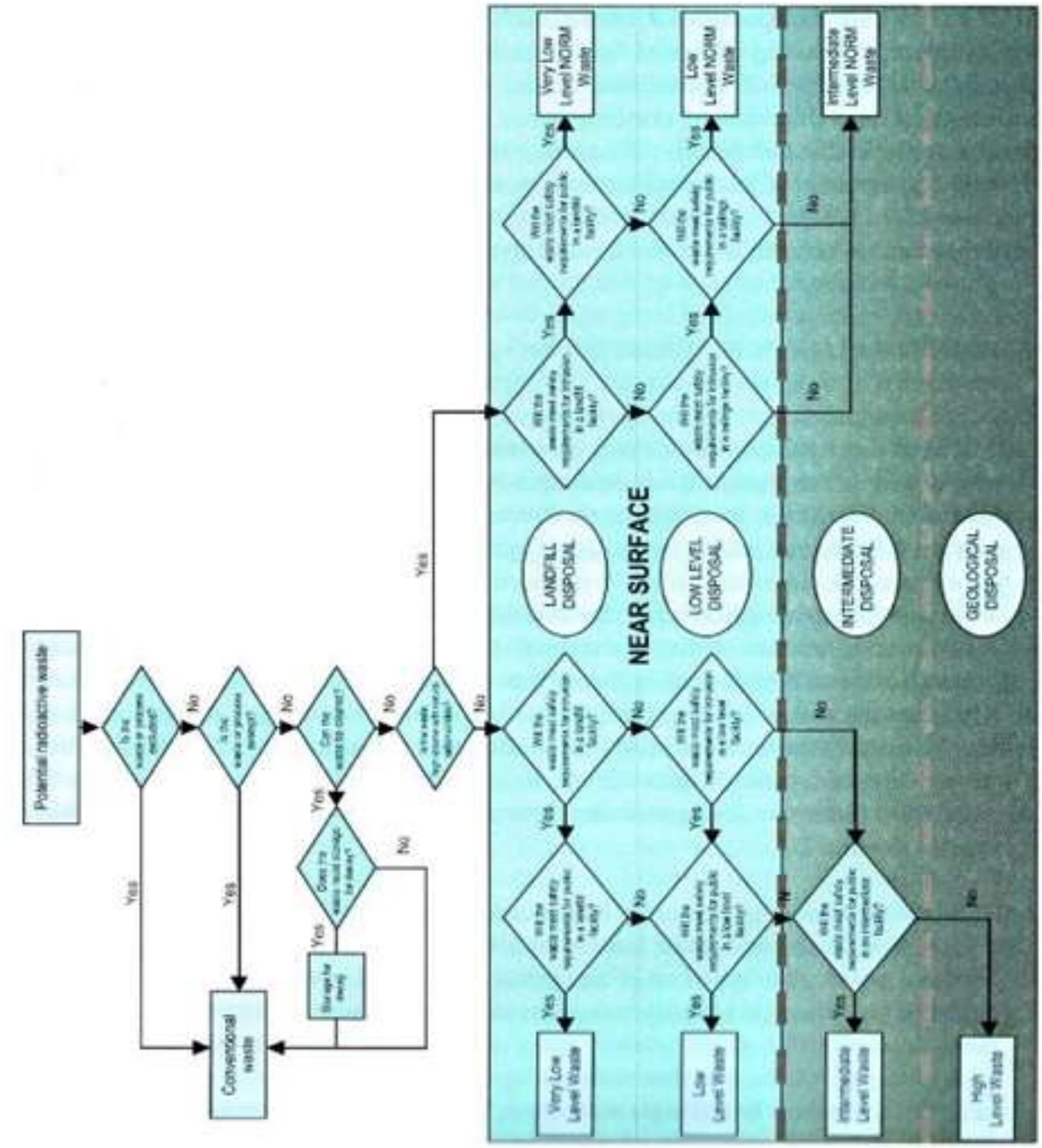

Fig. 2: An illustration of the classification scheme of radioactive wastes and modes of disposal (IAEA, 2009)

1. **Recycling:** This form of waste disposal involves the reuse of the radioactive materials. For example, radioactive wastes (HLW) containing uranium and plutonium is retrieved, reprocessed and reused, thereby extracting those radioactive elements from the materials to its barest minimum before finally disposing off by burial. Liquid wastes may equally arise from the reprocessing phases and are kept in vitrified glasses, prior to final disposal.
2. **Incineration:** This involves the disposal and burning of mostly low level wastes in incinerators owned by the plants or companies where the wastes are produced. Materials such as medical gloves, cloths, overalls, aprons, e.t.c (LLW) that has been contaminated by minor radiation are disposed in this manner.
3. **Storage:** Radioactive wastes depreciate over time, also known as "Radioactive Decay". During this process, the radioactivity of the material continues to decreases until it reaches a stage that it can safely be discarded. Nuclear plants, medical or research centres, industries or companies that deal with or produce radioactive materials/wastes have storage facilities in place for such purposes whereby radioactive wastes (LLW-HLW) are kept inside highly protected, tightly sealed dry containers neatly labeled and arranged in cupboards, cabinets, lockers, shelves, chests, etc. However, some of these materials are stored in non-corrosive (corrosion resistant) containers (wet method of storage), placed for storage in ponds or pools containing deionized water or inside concrete casks/vaults on dry land (dry method of storage) which is widely adopted (IAEA, 2018). It is noteworthy that some nuclear plants or research centres collect radioactive wastes from places and aid in storing them for a short to long period of time.
4. **Water Disposals:** Most countries around the world have industries that dispose wastes into the water, be it oceans, seas and rivers. They are classified as very low-level wastes (VLLW) with very low radioactive contents. The

wastes would be placed inside containers inform of missiles and embedded into the sea floor about 60-80m deep. This method was implemented by countries like the U.S.A, U.K, France, etc. This was later kicked against by the public as it could lead to water contamination/pollution if these containers eventually leak through the sea floor sediments. On the other hand, a controllable and inconsequential amount of liquid wastes retrieved during reprocessing or recycling phases are released into the waters by some industries. This was also eventually ruled out in the countries that carry out this act.

5. **Shallow or Near-surface Burials:** Very low-level, mill tailings, low-level and intermediate low-level wastes are most a times disposed this way. Pits of about tens of meters are excavated and the radioactive wastes are buried in them. They would be covered in mud or clay and a mixture of rocks. Example of countries that use this method of radioactive wastes disposal include the Czech Republic, France, Japan, Netherlands, Spain, UK, and USA. Sweden and Finland have near-surface facilities in caverns below ground level which are currently in operation (WNA, 2017).
6. **Deep Burials:** Here, wastes are disposed by burying them deep into the earth. An excavation of several hundreds to thousands of feet is made where these wastes would be buried. High-level wastes are disposed of this way, because they are highly hazardous to the public and the environment at large. A form of deep burial that is highly recommended for the disposal of such wastes is the "Deep Repository". However, not every reactor plant or industry situated in different parts of the world can afford to construct this, even as it has been tagged the best means of disposing highly radioactive wastes (BBC News, UK; 2006).

Other forms of radioactive waste disposal methods

Aside the already stated and discussed methods at which radioactive wastes can be disposed, several other ways were equally suggested to aid in properly discarding these wastes for a long term and from being a menace in the environment and to man.

1. **Out of space disposal:** This involves the complete removal of radioactive waste materials from Earth. These are first treated then well packaged and launched into space via rocket/space launchers. This mode of disposal is made for ridding off high level wastes in small volumes. However, this was abandoned after it was realized to be highly expensive and the tendency of the launching process failing. Out of space disposal was initially investigated and planned to be implemented by United States of America, but never came to be.
2. **Long-term above ground disposal:** An "interim" means of disposal is provided for keeping away radioactive waste materials. These temporary waste facilities are built on the surface and the radioactive wastes are stored for a period of time prior to when a long-term form of disposal is created. If need be, some radioactive materials could still be retrieved easily if stored in this medium, though, the facility would be constantly checked and monitored by security personnel, safeguard and supervision procedures would be handled by professionals. This method was investigated in France, Netherland, Switzerland, United Kingdom and United States of America. However, it is not planned to be implemented anywhere for now.
3. **Rock melting form of disposal:** Radioactive wastes (especially HLW) are encapsulated and injected into an excavated rock. The heat emanating from the waste through the container would melt the wall rock and would project further downwards. However, the rock would recrystallize and solidify above the container, and the radioelements emitted would remain within the rock. This method was studied and investigated in the United Kingdom, Russia and United States of America, but was not implemented.
4. **Deep well injection:** This involves direct drilling of treated or untreated radioactive waste products (LLW, ILW and HLW mostly in liquid form) through geologically stable, porous and permeable rocks. The injection and release of the wastes are executed at depths greater than 1000 feet from the surface, through water aquifers (i.e. below water aquifers). The rock formation is bounded vertically and horizontally by impermeable strata to prevent migration of the radioactive wastes from contaminating ground/drinkable water. Double concrete casings (surface and inner casings) are made to prevent contamination of the ground water and movement/escape of the waste respectively, before getting to the expected depth. This was implemented in Russia, investigated upon and later abandoned by the United States of America.
5. **Disposal in ice sheets:** This disposal method is carried out in icy regions, whereby the radioactive waste materials are injected into a drilled ice. Over time, the opening above is sealed by a newly formed ice mass, therefore sealing the waste. However, the heat emanating from the radioactive waste melts the ice below it and gets sunk deeper and deeper into the icy body and the method by which a new ice conceals the spaces created is repeated.
6. **Disposal in oceans:** Oceans have been taken by some countries as a body mass that can absorb radioactive by-products, especially very low, low and intermediate level wastes. These materials firmly sealed in an air tight container and dropped into the sea and submerge onto the sea bed. However, these containers may begin to wear off and radioisotopes would make ways to escape from the containers into the water if care is not taken. Nevertheless, the concentration of radioisotopes would decrease as a result of radioactive decay and the dilution with the water body over a long period of time. This was implemented in Russia, Belgium, Italy, France, Germany, Japan, Netherland, South Korea, United Kingdom, United States of America and Switzerland. However, this method of disposal has raised great concerns and has been stopped over international agreements.
7. **Sub-sea bed disposal:** This involves burying radioactive wastes (ILW, LLW and/or HLW) beneath the sea floor. This is done directly or indirectly by constructing repository beneath the ocean floor which would be accessed through channels linked from land; or the corrosion resistant containers containing the wastes either penetrate through the sea floor themselves when dropped into the sea with a great force to a depth greater than 50 m; or holes (about 800 m deep) are drilled through the seafloor sediments and the containers are injected into the holes and sediments with a thickness of 300 m conceals the containers in the holes. In an advent whereby radionuclides escape or the container leaks, the materials would not be so harmful as the elements are continuously undergoing radioactive decay, diffusion, absorption, dispersion and the water also serves as a diluting medium, decreasing the radioactivity of the elements. This method of disposal is better than just dropping the wastes on the seafloor. This method was however investigated in Sweden, United Kingdom and the Organization for Economic Co-operation and Development Nuclear Energy Agency but was not

implemented nor agreed upon by international governments.

8. **Disposal in subduction zones:** Subduction zones are zones on the Earth's crust where two crustal plates converge or collide and the thicker one gets subducted below the less thick crust. This gives rise to formation of deep trenches which are considered by scientists to be able to house radioactive waste materials several kilometers from the water surface. As the denser crust continues to get subducted, it carries along with it the wastes deeper and further below the ocean floor. This has been investigated to be a possibility by several countries example by the United States of America, but has not been implemented or permitted.
9. **Borehole disposal:** Borehole disposal is somewhat similar to the deep well injection form of disposal, the differences being that the borehole method involves both liquid and solid forms of waste (spent nuclear fuel and high level wastes especially those rich in Cs/Sr), and the depth of boreholes is far greater than that of a deep well (to a depth of 5 – 100 km) (Fig. 3) (Van Blerk *et al.,* 2000). It is drilled through permeable rock formations, water aquifer region to an impermeable non-porous lithology of hard crystalline basement rock or lithology having a high concentration of brine, as it prevents upward flow of water into the overlying water aquifer. The deep boreholes are sealed by injecting cement, bentonite or by rock-welding (that is, partially melting granitic rocks to weld breakages, openings or fractures. Deep borehole disposal is being examined as an option for radioactive waste disposal by researchers in the US, the United Kingdom, China, Germany, South Korea, and Australia.
10. **Deep geological repository:** Deep geological disposal of radioactive waste presents a critical review of designing, sitting, constructing and demonstrating the safety and environmental impact of deep repositories for radioactive wastes. Emphasis is very much on "deep" geological disposal – ranging from hundreds to thousands of meters deep. Additionally, only radioactive wastes are considered directly – even though such wastes often contain also significant chemo-toxic or otherwise hazardous components. Many of the principle involved are generally applicable to other repository options (e.g. near-surface or on-surface disposal) and, indeed, to other types of hazardous waste (IAEA, 2003). As already stated above, the various types of radioactive wastes have means to which they are best disposed, but the high-level waste is best disposed via deep geologic repository. It is highly favored although the main challenge is how and where the facility should be constructed. The high to intermediate level wastes kept in this form are those that need not to be retrieved, reprocessed nor recycled because they are placed at hundreds and thousands of feet down below, hindering easy access to the materials.

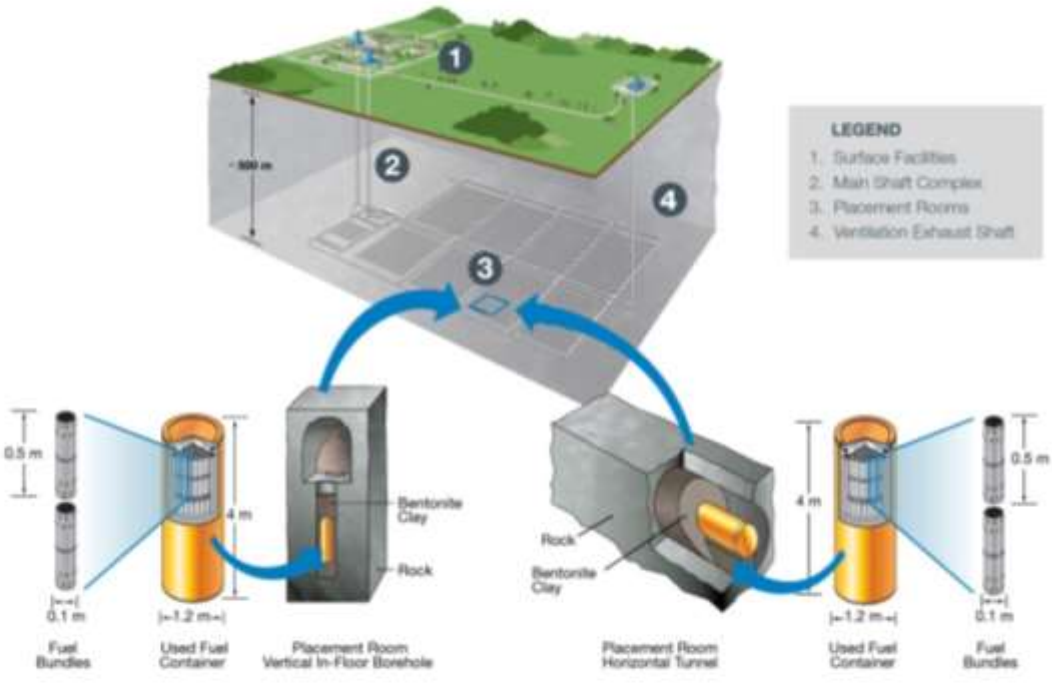

Fig. 3: Diagram of deep geologic repository with used fuel containers and bentonite sealing (Keech *et al.*, 2014)

Conclusion

The level of radioactive wastes generated from one facility or plant to the other varies, thus, each have their means by which wastes are disposed. These materials are to be handled with care, be they low or high level wastes. Exposure to radiation increases gradually from minute contacts of these materials by handlers, which can be nonchalantly disposed. High level wastes or spent nuclear fuels are highly radioactive but when retrieved, reprocessed and recycled, their level of radioactivity is reduced before final disposal. Getting rid of these waste materials via incineration, into water and space are not proper means of disposal because radioelements are released into the atmosphere, hydrosphere and biosphere, thus, becoming hazardous to both living creatures and the environment at large. Hence, appropriate storage, containment and burial serve best to discard radioactive waste materials.

Conflict of Interest

Authors have declared that there is no conflict of interest reported in this work.

References

Andra 2016. French National Radioactive Waste Management Agency. Meuse and Haute-Marne Centre.

Barney GS 1992. Radioactive wastes. Encyclopedia of Physical Science and Technology. 2nd edition, Vol: 14, San Diego, p. 109.

Biello D 2011. Presidential Commission Seeks Volunteers to Store US Nuclear Waste. *Scientific American*. Archived from the Original on 2014-02-26.

Carter IJ 1987. Nuclear imperative and public trust: Dealing with radioactive wastes. *J. Storage: Issues in Sci. and Techn.*, 3(2): 46-61.

Clark S & Ewing R 2006. Panel 5 Report: Advanced waste forms. *Basic Research Needs for Advanced Energy Systems*, pp. 59–74.

Findlay T 2010. Nuclear Energy to 2030 and its Implications for Safety, Security and Nonproliferation: Overview *(PDF). Nuclear Energy Futures Project.* Archived (PDF) from the Original on 2014-03-07.

Ian Hore-Lacy 2010. Nuclear Waste Management (*The Encyclopedia of Earth*, 25 July 2010) http://www.eoearth.org/article/Nuclear_waste_management#gen1

International Atomic Energy Agency 2003. Remediation of Areas Contaminated by Past Activities and Accidents: IAEA Safety Standards Series No. WS-R-3, IAEA, Vienna

International Atomic Energy Agency 2009. Classification of Radioactive wastes. *IAEA Safety Standard Series*, No: GSG-1; ST1/PUB/1419.

International Atomic Energy Agency 2018. Nuclear Energy Series Publication. Status and Trends in Spent Fuel and Radioactive Waste Management, No. NW-T-1.14.

Jablonski SM 2004. Radioactive Waste. Pollution, A to Z (*Encyclopedia*, 2004) http://www.encyclopedia.com/doc/1G2-3408100213.html

Jack T & Robertson J 2008. Utah nuclear waste summary. *Salt Lake City: University of Utah Center for Public Policy and Administration.* Archived from the original (PDF) on 2008-12-16. Retrieved 2008-12-24.

Kademani BS, Surwane G, Sagar A, Mohan L & Bhanumurthy K 2013. Research trends in radioactive waste management; a global perspective. *International Journal of Low Radiation*. 9(1): 59-94.

Keech PG, Vo P, Ramamurthy S, Chen J, Jacklin R & Shoesmith DW 2014. Nuclear waste management organization (NWMO) Deep Geologic Repository concept. Design and development of copper coatings for long term storage of used nuclear fuel (UNF). *Corrosion Engr. Sci. and Techn.*, 49(6): 425-430.

Klein JA 1991. Nuclear waste management. *Encyclopedia of Applied Physics*, 12: 2.

Mederal JM 2011. Radioactive waste Management in the European Union. LL.M Paper for the Masters of Law in European Law, Gent University. A Published Masters Research Work, pp. 1 – 66.

Rao KR 2001. Radioactive waste: The problem and its management. *Current Science,* (81): 1534–1546. Retrieved 2008-12-24.

Rogner HH 2010. Nuclear power and sustainable development. *Journal of International Affairs,* 64(1): 137-163.

Thomas KT 1981. Management of wastes from uranium mines and mills. *International Atomic Energy Agency Bulletin*, 23(2): 33–38.

US Department of Energy, Carlsbad Field Office 2003. Why Waste Isolation Pilot Plant (WIPP).

US Nuclear Regulatory Commission 2017. Backgrounder on Radioactive Waste. Archived from the original on November 13, 2017. Retrieved December 3, 2017.

Van Blerk JJ, Vivier JJP, Andreoli MAG & Heard RG 2000. The Borehole DisposalConcept for Spent Sources - Volume I: Development and Evaluation of the Concept. Atomic Energy Corporation of SA. Internal Report No. GEA-1353, Pretoria.

World Nuclear Association (WNA) 2017. Radioactive Wastes: Myths and Realities.

World Nuclear Association (WNA) 2018. Radioactive Waste Management.

World Nuclear Association (WNA) 2018. Storage and Disposal of Radioactive Wastes.