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CERTAIN ASPECTS OF HIGH LEVEL RADIOACTIVE WASTES – A BRIEF NOTE ON THE PROBLEM

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Issues of high level nuclear waste disposal which involve a number of known and unknown risk factors are discussed. Implementation of nuclear waste disposal has to be based on multi-criteria decision making. Some of the major aspects of the issues are analyzed and described briefly to build a perception of the ethical implications and risks involved. This brief account on state of the nuclear waste disposal problems would be helpful for researchers working on radioactivity containment and disposal.

Keywords: Radiation effects, Radioactivity leakage, Engineered barrier systems, Earthquake, Leaching, Thermodynamic equilibrium, Environment ethics, Nuclear energy

1. Introduction

Nuclear energy is one of the important energy forms in use like hydel, coal, nuclear, oil, gas and wind [1-4]. Nuclear energy has some special features, especially it is considered as a solution to climate change, abundant fuel and no dependence of supply on seasonal changes. Safe development of the affiliated technologies assures state of the art development of nuclear power, which is considered attractive by the developing countries like Pakistan, India and China. However, further extension of nuclear power worldwide is limited due to still unresolved nuclear waste management issues [5-11]. After many decades of active operation of nuclear power stations, a final successful policy of nuclear waste disposal could not be developed as high level nuclear waste (HLNW) disposal may have extremely serious implications if disposal implementation fails due to engineering faults or natural disasters like high magnitude earthquakes leaking radioactivity into the Environment. The Environment here refers to the air, the water and the soil.

Only a very limited number of countries like Sweden have finalized their policy about definition of nuclear waste [12,13], abandoning the possibility of reprocessing, whereas the remaining nuclear world is still un-decided on whether they will dispose off as-taken-out spent nuclear fuel (SNF) or only reprocessed waste. So, the problem of nuclear waste disposal needs to be analyzed critically with the motivation of achieving a clear resolve to it. This brief paper points to certain aspects of a few major problems associated with high level nuclear waste disposal.

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2. High-Level Nuclear Wastes

Major fraction of the high level nuclear waste is the spent fuel in commercial nuclear power plants. When it comes out of reactor core, it is very strongly radioactive and one of the most hazardous materials known. Its radioactive strength decreases with time due to decay reactions, but unfortunately its hazardous life is many orders of magnitude higher than the known history of human civilization. Depending upon country’s policy, as-taken-out spent nuclear fuel or reprocessed waste is treated as a nuclear waste. It may be noted that reprocessing [14-16] extracts isotopes, such as ^{239}Pu in case of uranium fuel and ^{233}U in case of thorium fuel, from spent fuel that can be used again as reactor fuel.

Normally, uranium is used as a nuclear fuel in power reactors. Fig. 1 shows the general composition and forms of fission products and trans-uranium elements in spent nuclear fuel.

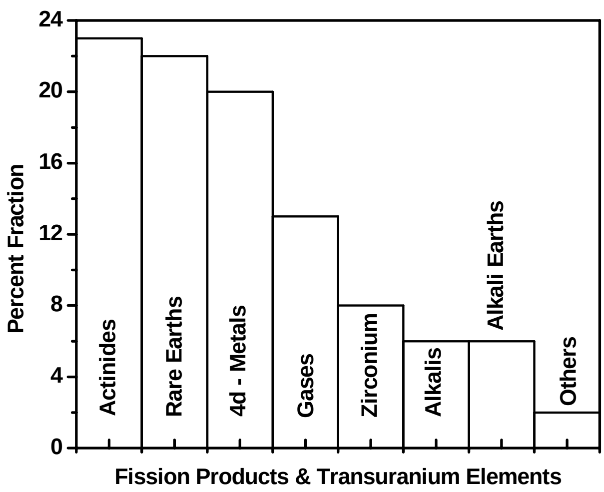

Figure 1. General composition and forms of fission products and transuranium elements, which are most important in evaluation of disposal activity. Presentation is based on results by Buck et al. [10].

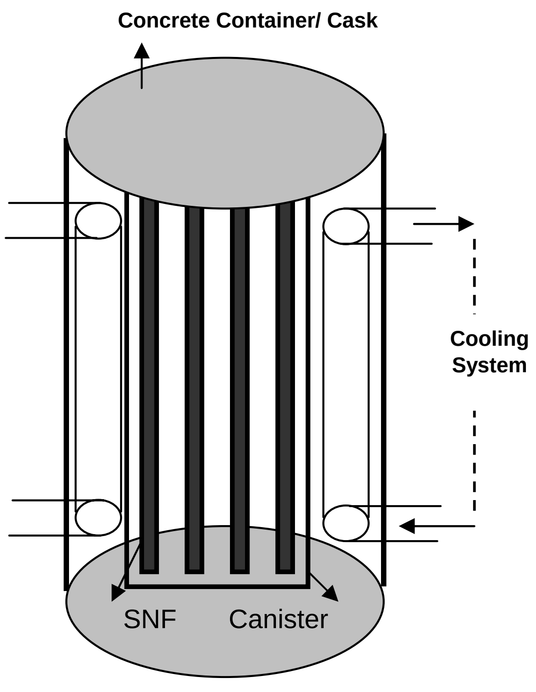

Figure 2. Conditioned spent nuclear fuel showing the need of its cooling.

Apart from radioactivity, spent nuclear fuel is also thermally hot and need adequate cooling for a certain period of time to maintain integrity of the fuel. Integrity of the burnt fuel is required as it provides better control in isolating the radioactive nuclides in fuel from the safe environment. Broken integrity of SNF makes reprocessing difficult as it can alter the distribution of the still burnable nuclides, like ^{239}Pu and ^{233}U in it. Fig. 2 is a spent fuel assembly showing the need of cooling. Each individual assembly in the storage needs adequate cooling and is commonly achieved by keeping spent fuel in a cooling bay, but even after final disposal, spent fuel may need cooling to restrict movement of radionuclides which may become more probable after thermal meltdown.

Nuclear fuel used in power reactors is in solid form. Radioactive gases may be emanated from spent fuel. It can melt down thermally or can be dissolved in a liquid. So, HLNWs can possibly be in any of gas, liquid and solid forms or mixture of them. Their physical and chemical properties would vary in different forms. So, their routes and levels of hazard in different possible forms need to be evaluated. Deterioration and transformations in spent nuclear fuel due to spontaneous decay, containment conditions and combined effects should also be examined.

3. Radiation Effects

Degradation of spent fuel itself and containment materials due to radiation effects is a very considerable concern. Intensive radiation exposure causes dramatic degradation in structural and strength related properties of materials leading to their failure when damage exceeds a certain limit. A number of aspects of radiation damage have been recognized and being studied over more than 60 years [17-18]. Radiation damage leaves four types of effects on any material, i.e. electronic and optical which are not significant in nuclear waste containment, physical and chemical. Physical and chemical effects need to be considered. A variety of radiations continue penetrating waste containment and the aggregated effects over decades thus are important for determination of containment failure. A single radiation, especially energetic charged particle, causes a compound spike [19] in the target material. This compound spike arises as a consequence of a Coulomb explosion and a thermal spike, and decays very quickly within 10^{-12} s. These physical impacts result in the form of heat emitting out into the neighbouring material of the cylindrical zone through which radiation passes. The increased temperature, due to continuous radiation spikes, produce chemical changes like formation of new material phases [20-21]. Fig. 3 shows the generalized view of expected radiation effects on

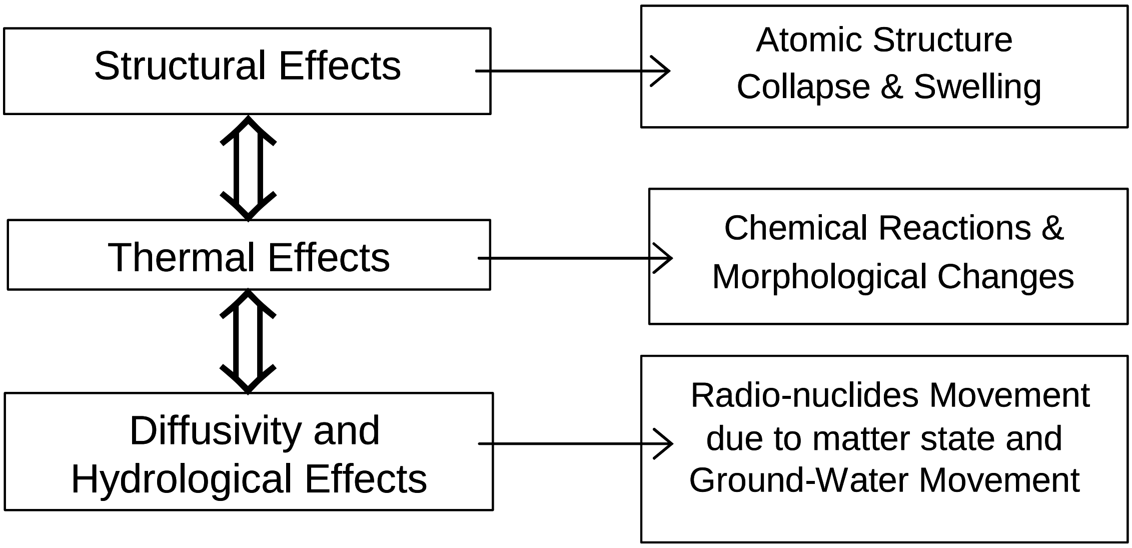

Figure 3. Radiation effects on containment materials and environment.

containment materials to be used in nuclear waste disposal.

It is extremely important to monitor the radiation damage in nuclear waste canister and containment walls to predict the fail-safe period for the containment. Recently, the author introduced [2] new technique/method, based on ion channelling, for monitoring the radiation damage in nuclear waste immobilizing materials like zircon. This method makes use of proton/ion channelling measurements of the crystalline containment sample or test crystalline sample placed in the crystalline or amorphous containment of nuclear waste for a long time from years to a few decades and the mathematical model to determine the structure collapse rate of the containment material using channelling measurements. The technique makes possible the quantification of radiation damage accumulation over long periods of time and will help in improving nuclear waste management. Ion beam channelling facility (on site or remote) is the major high finance requirement for implementation of the whole radiation damage monitoring process [22]. There are a number of ion beam facilities around the world [23], which can be utilized for this purpose and will need an operation of a few hours in a year or so.

Here, a very brief account of basic physics of radiation damage is being given which may help in implementation of the method for the radiation damage monitoring described above and interpretation of experimental observations of the method. A charged particle or radiation travelling in a solid creates a superheated cylindrical zone with a modified structure containing defects of various types and size. In the inner dotted cylindrical zone in Fig. 4, bulk atomic flow takes place whereas in the outer shell only individual atomic flow is occurred. A fresh radiation damaged zone in a solid is highly unsteady in time and after reaching thermodynamic equilibrium it becomes an inhomogeneous structure. The energy deposited by the incident radiation in a cylindrical volume around the path is non uniform. It decreases exponentially along radial direction whereas distribution along axis of the cylinder depends on energy of the particle. For an MeV/u ion, it has a maximum at a depth into the target.

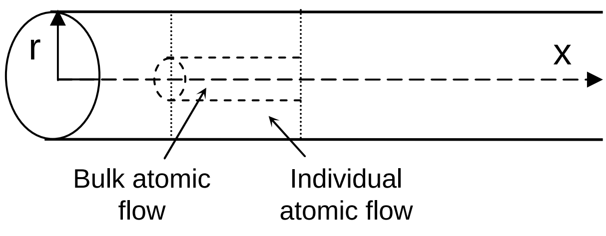

Figure 4. Radiation damage produced by a charged radiation in a typical solid, showing cylindrical zones of bulk and individual atomic flows. Parameters are defined/shown in this figure for the purpose of mathematical description of the problem.

Interaction of a radiation with a solid target can be treated as a compound spike including partial roles of both thermal and Coulomb explosion spikes [19, 24]. Fractional roles of both spikes depend on atomic and electronic structure of the target and density of deposited energy in it by the incident radiation. An incident radiation is scattered by the atoms in the target as it interacts with them and deposits energy. Weak scattering of incident radiations by light target atoms does not significantly deviate incident particles from their straight trajectories while the target atoms recoil considerably, damaging the detector. Heavier atoms scatter incident particles through wide angles, significantly deviating them from their straight paths while the target atoms recoil weakly, producing less damage [25]. So, it is important to notice that radiation damage mechanism in a target composed of light atomic species is different from that composed of heavier atoms. Compound impacts of a number of radiations in a target, incident within a specific distance, superimpose with one another in both constructive and destructive manners. Part of the damage produced by one radiation is extended due to the damage produced by another radiation within a few hundred nanometres. Nuclear waste containers and related materials are exposed to radiations with a wide spectrum of ionizing power including fission fragments of very high ionizing power and gamma rays of comparatively very low ionizing power.

4. Challenges in Transport and Disposal of High-Level Nuclear Wastes

Radioactive or nuclear wastes need to be transported to storage, processing and disposal sites. Transport procedure is planned and implemented considering several factors. These factors include composition, quantity and types or forms (gas, liquid and solid) of the waste, quantitative analysis of leakage of the waste and radiation exposure of the occupational operators and general public. Other concerns are the possibilities of accidents and ill-will, their consequences and the preparedness to cope with such situations. Temporary storage of nuclear wastes at production sites is basically aimed at reduction of the awful implications of the failures during transport and disposal. It also reduces costs of transport and disposal.

Characteristics of nuclear wastes such as chemical composition, decay life and material type or form (gas, solid and liquid) are of fundamental importance in implementation of their storage, packaging, transport and disposal. The scientific community working on nuclear waste management has come up with three practical methods for management of high level nuclear waste which are surface storage, deep geological disposal, and partitioning and transmutation. Surface storage which is being done successfully worldwide is only a temporary solution. Deep geological disposal is being evaluated and designed, but has not been started yet. Partitioning and transmutation is the third option which does not provide a complete solution to the problem of nuclear waste disposal. It can, of course, reduce the degree of dangers associated with high level nuclear wastes by burning off long lived radioactive species in the waste by using fast reactor or accelerator driven systems. In this method, different radioactive species in the nuclear wastes need to be partitioned for placing them in different regions in special power plants called Accelerator Driven Systems (ADS) [26,27] with optimum neutron energy for transmutation of each of them. These plants have their own complications as yet. The nuclear waste treated this way will still need deep geological disposal. Two significant options, which are now being considered rejected due to technical difficulties and lack of present knowledge and resources, are the space disposal or dumping into the outer space and ocean disposal. Space disposal might become a realistic possibility using a radioisotope-powered space mission [28]. It seems logical to know the merits and demerits of all the disposal options for high level nuclear waste disposal in a certain set of conditions which would help in deciding about the agreeably suitable ones. All radioactive waste disposal programs around the world face some general problems, but usually there are also very specific problems within each national program which dictates the individual challenges confronted by individual countries.

It is extremely difficult to generalize these challenges and engineering solutions. Initial radiation strength per unit volume or mass of the SNF depends on burn up of the fuel, but extremely high for any living being without best available shielding arrangements [29]. The SNF remains radioactively hot at geological time scale up to millions of years. Types of radiations include charged and neutral particle rays, and electromagnetic radiations. Decay of radioactive elements in the SNF is accompanied with the release of energy, most of which is transformed into heat. The SNF is a heat source which can harm integrity of its disposed packages. Thirteen percent of fission products and transuranium elements are gases [10], which has higher danger of leakage and emanation into the objectively safe environment. Direct disposal of SNF will be cheaper [30]. Reprocessing decreases the danger level of SNF, but does not solve the problem completely. Final disposal will still be needed [29]. Ideally, retrievability after disposal is required. But, its assurance is difficult due to involvement of unexpected natural happenings like earthquakes.

5. Earthquakes and Surface Ruptures at Waste Storage and Disposal Sites

Major concern about nuclear technology is safety. Safety failure can be disastrous. Earthquakes are a reality and are completely un-predictable to challenge the safety. Countries with nuclear technology consider earthquake factor in maintaining their nuclear technology and related facilities, and such future plans. Figures 5 and 6 show fissures in the ground are visible in front of the Kashiwazaki nuclear power plant and black smoke rising from the same nuclear plant due to earthquake on July 17, 2007 [31]. IAEA sent a team to Kashiwazaki-Kariwa Nuclear Power Plant after earthquake, which concluded that plant safety features had performed as required during the earthquake event, but the earthquake significantly exceeded the level of seismic activity for which the plant was designed. According to their report, the

Figure 5. After earthquake, Kashiwazaki nuclear power plant [31].

Figure 6. Smoke rising from the nuclear plant on July 17, 2007 [31].

amount of radioactivity released was very small and well below the authorized limits for public health and environmental safety. But, it was pointed out that the observations and conclusions relating to the behaviour of the plant structures, systems and components still require validation through the valid procedure [32].

Earthquake also is an important consideration in site selection and design of a spent nuclear fuel storage or repository. Engineering/geographical aspects of spent nuclear fuel disposal have been discussed (e.g., a brief overview in [18]). Shaking table tests [33] may be employed to estimate the properties of the test frame at frequencies related to earthquake. Earthquake can cause Tsunami in coastal areas [34,35]. So, history of earthquakes and their consequences in the site under consideration need to be evaluated carefully. Severe earthquakes can contaminate earth surface with temporarily stored or finally disposed nuclear waste, which requires trustworthy understanding about migration/leaching of radionuclides on earth surface and nature of traps for their accumulation [36-38]. Disequilibria of U-series and radiation induced effects in minerals may be used in safety analysis of nuclear waste disposal [39,40].

6. Thermodynamic Equilibrium and Multi-barrier Isolation

Thermodynamic equilibrium is a state of a system related to the minimum of the thermodynamic potential. Thermodynamic potential is the Helmholtz free energy (U – TS) for systems at constant temperature and volume whereas the Gibbs free energy (H – TS) for systems at constant pressure and temperature. U, T, H and S are, respectively, internal energy, absolute temperature, enthalpy and entropy. Minimum of thermodynamic potential is characterized by states of thermal equilibrium, mechanical equilibrium and chemical equilibrium of the system. Ideally, nuclear waste should be disposed in a way that it becomes in thermodynamic equilibrium with the environment and remains the same for almost forever without losing its original integrity.

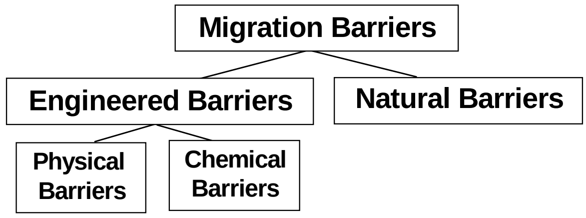

Figure 8. An overview of the possible barriers to confine or isolate the disposed high level nuclear waste from biosphere.

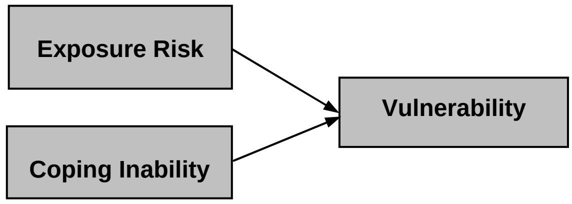

Figure 7. Definition of the human vulnerability.

Success probability of SNF disposal would increase by implementing multiple barrier [29] strategy to confine the disposed waste and its effects far from safe environment to which living being have or may need to have contact in future. The definition of human vulnerability in such a case is given in Fig. 7. Fig. 8 gives an overview of possible barriers to confine the disposed high level waste. Most important of natural barriers is a solid stable crystalline rock far from seismic zones. Engineered barriers include corrosion-resistant containers possibly of copper alloys (containing mainly copper alongwith Al: 5 to 9%; Ni: 0.5 to 4%; Fe: 0.5 to 4%; MN: 0.1 to 3%; Ti: 0.001 to 1%, Co: 0.001 to 1%; and B: 0.001 to 0.1% [41]) and disposal architecture. Regular drilled-hole monitoring in the buffer zone and sampling the leached activity before and after earthquake can establish underground faults produced due to earthquake. Nuclear waste containment and the over-all repository environment should ideally be as close as possible to thermodynamic equilibrium, meaning unlimited stability, similar to natural metal deposits within Earth's crust [42].

7. Environment Ethics

Some of major considerations in evaluation of ethical issues related to safety of nuclear waste disposal are clarity of the policies, policy awareness of individuals involved, natural response to nuclear fear/risk factor and valid legal system to sue charges. Central specific ethical issues are summarized as a set of disposal activity start-up questions [43-46]: (1) Have the persons employed/ involved been given the free informed consent to the risk involved? (2) Who bear major responsibilities in waste disposal and who is responsible for what? (3) Are the distributions of risks and benefits equitable? (4) Have individuals been informed about control over the risk? (5) Are assessment about reliability of materials and methods involved are made? (6) What are the third parties who can be held responsible for bringing in risk? (7) Evaluation of costs and benefits of intervention measures? (8) Are the plans of compensation for exposure to risk justified? (9) How will an emergency be handled? Generalizing theme build up by above questions, it may be said that issues like consent, equity, control and responsibility are essential ethical considerations for radiological protection policy [47].

It would be interesting to know how above issues or questions about nuclear waste disposal are incorporated in policy making and its implementation. Only thoughtfully critical and multi-ply reviewed process of policy analysis can achieve this. Ethical issues are closely linked with scientific or technical know how about procedures involved. So, a trustworthy research is needed to finalise ethical aspects of high level nuclear waste disposal. Evaluation of risk faced by far-future generations due to present disposal of high level nuclear waste is also of great importance and equally valid ethical issue as for the case of present generation. Real problems are associated with predictions about level and nature of risks faced by future generations and their response to this problem, especially in case of disposal failures.

It would not be wise to dispense with highly radioactive material and to hope that either nature or future generations of humans will not bring it into the biosphere somehow. In principle, we should ensure that even if detail of nuclear waste disposal is lost and does not reach future generations, still they or their environment is not exposed to disposed waste at all. Nuclear waste disposal in one country can quite possibly affect biosphere in the neighbouring countries. Pakistan’s two neighbouring countries (India and China) are among the countries seeking sizeable future nuclear energy programs [48] whereas Russia has offered its land for a multinational nuclear waste repository [49]. These activities may pose questions of nuclear security and environmental justice which Pakistan would need to address. Nuclear waste disposal is not a solely internal matter of any country. Activity of nuclear waste disposal may have strong local, regional and even global implications. Regional and global implications would become considerable for the cases of severe failures of disposal scheme.

8. Present Status

Table 1 summarises the present plans for high-level nuclear waste repositories. Tabulated details

Table 1. Plans for high-level nuclear waste repositories [11]

Country	Geological medium	Estimated opening	Status
Belgium	Clay	2035 or later	Searching for site
Canada	Granite	2035 or later	Reviewing repository concept
Finland	Crystalline bedrock	2020	Site selected (Olkiluoto)
France	Granite or clay	2020 or later	Developing repository concept
Germany	Salt	Unknown	Moratorium on development
Japan	Granite or sedimentary rock	2030 or later	Searching for site
Russia	Not selected	Unknown	Searching for site
Sweden	Crystalline rock	2020	Searching for site
Switzerland	Crystalline rock or clay	2020 or later	Searching for site
United Kingdom	Not selected	After 2040	Delaying decision until 2040
United States	Welded tuff	2010	Site selected (Yucca Mountain)

show the sensitivity of the subject and requirement of the decades-long considerations before start up of implementation of any disposal policy. In nuclear waste disposal matters, four considerations are very important which are radiation strength, mean life, environment contamination and traditional ethical values. Ethical values here refer to rightness or wrongness of our actions. Considering above discussion about high-level nuclear waste disposal, a long time in decades would be needed for the evaluation of repository location, design and precautions before start up of disposal. Careful record keeping (including details of professionals involved) of all nuclear waste disposal evaluations should be practiced so that investigation of possible accident/emergency could be carried out with transparency.

Clear demonstration about safety aspects of nuclear waste management would help in gaining public and political confidence in any possible scheme of permanent nuclear waste disposal. A common public desire is retrievability of finally disposed wastes in case repository fails to isolate wastes from the live environment. Desire of retrievability is in direct contradiction with the principle of final disposal and adds serious complexities to the problem. Public resistance against nuclear waste repository [50] at Yucca Mountain [51] is a typical example showing the complexities involved.

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