AERB SAFETY GUIDE NO. AERB/SG/S-4

HYDROGEOLOGICAL ASPECTS OF SITING OF NUCLEAR POWER PLANTS

Issued in September, 2000

This document is subject to review, after a period of one year from the date of issue, based on the feedback received.

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FOREWORD

Safety of public, occupational workers and the protection of environment should be assured while activities for economic and social progress are pursued. These activities include the establishment and utilisation of nuclear facilities and the use of radioactive sources. They have to be carried out in accordance with relevant provisions in the Atomic Energy Act, 1962.

Assuring high safety standards has been of prime importance since inception of the nuclear power programme in the country. Recognising this aspect, the Government of India constituted the Atomic Energy Regulatory Board (AERB) in November 1983 vide Statutory Order No. 4772 notified in the Gazette of India dated 31.12.1983. The Board has been entrusted with the responsibility of laying down safety standards and framing rules and regulations in respect of regulatory and safety functions envisaged under the Atomic Energy Act of 1962. Under its programme of developing safety codes and guides, AERB has issued four codes of practice in the area of nuclear safety covering the following topics:

Safety in Nuclear Power Plant Siting

Safety in Nuclear Power Plant Design

Safety in Nuclear Power Plant Operation

Quality Assurance for Safety in Nuclear Power Plants

Safety guides are issued to describe and make available methods for implementing specific parts of relevant codes of practice as applicable to AERB. Methods and solutions other than those set out in the guides may be acceptable if they provide at least comparable assurance that Nuclear Power Plants (NPPs) can be operated without undue risk to health and safety of plant personnel, the general public and the environment.

Codes and Safety Guides may be revised as and when necessary in the light of experience as well as relevant developments in the field. The annexures, footnotes, references and bibliography are not considered as integral parts of the document. These are included to provide information that might be useful to the user.

Emphasis in the codes and guides is on protection of site personnel and public from undue radiological hazards. However, for other aspects not covered in the codes and guides, applicable and acceptable national and international codes and standards shall be followed. In particular, industrial safety shall be assured through good engineering practices and through compliance with the Factories Act, 1948 as amended in 1987 and the Atomic Energy (Factories) Rules, 1996.

This Safety Guide, Hydrogeological Aspects of Siting of NPPs, is one of a series of guides prepared or are under preparation as a follow-up to the Code of Practice on Siting for Safety in Nuclear Power Plants (AERB/SC/S) and outlines the methodology and procedures for carrying out analysis as applicable for implementing relevant parts of the Code of Practice.

This Safety Guide has been prepared by the staff of AERB, BARC and NPC. The criteria followed by DAE for selection of a site and the relevant International Atomic Energy Agency (IAEA) documents under the Nuclear Safety Standards programme, especially the Hydrogeological Aspects of Siting of NPPs (50-SG-S7 of IAEA) and similar documents from various leading countries, suitably adapted to Indian conditions have been utilised extensively in preparation of this Guide. It has been reviewed by experts and vetted by the AERB Advisory Committees before issue. AERB wishes to thank all individuals and organisations who have prepared and reviewed the draft and helped in the finalisation of the Safety Guide. The list of persons who participated in the committee meetings, along with their affiliation, is included for information.

Suhas P. Sukhatme

(Suhas P. Sukhatme)
Chairman, AERB

DEFINITIONS

Atomic Energy Regulatory Board (AERB)

A national authority designated by the Government of India having the legal authority for issuing regulatory consent for various activities related to nuclear facility and to perform safety and regulatory functions including enforcement for protection of the public and operating personnel against radiation.

Normal Operation

Operation of a plant or equipment within specified operational limits and conditions. In case of nuclear power plant this includes, start-up, power operation, shutting down, shutdown state, maintenance, testing and refuelling.

Nuclear Power Plant

A thermal neutron reactor or reactors together with all structures, systems and components necessary for safety and for the production of power, i.e. heat or electricity.

Operation

All activities following commissioning and before decommissioning performed to achieve, in a safe manner, the purpose for which the plant was constructed, including maintenance.

Region

A geographical area, surrounding and including the site, sufficiently large to contain all features related to a phenomenon or to the effects of a particular event.

Regulatory Body

See 'Atomic Energy Regulatory Board (AERB)'.

Safety

Protection of all persons from undue radiological hazards.

Site

The area containing the facility, defined by a boundary and under effective control of facility management.

Siting

The process of selecting a suitable site for a facility, including appropriate assessment and definition of related design bases.

SPECIAL DEFINITIONS

(Specific for the Present Guide)

Aquiclude

Formation which, although porous and capable of absorbing water, does not transmit it at rates sufficient to furnish an appreciable supply for a well or spring.

Aquifer

Porous water-bearing formation (bed or stratum) of permeable rock, sand or gravel capable of yielding significant quantities of water.

Conductivity, Hydraulic

Combined property of a porous medium and the fluid moving through it in saturated flow, which determines the relationship, called Darcy's Law, between specific discharge and head gradient causing it.

Diffusion Coefficient (Porous media)

Amount of solute that passes across a unit cross-section in a porous medium in unit time under the influence of a unit concentration gradient.

Diffusivity, Intrinsic porous media

A geometric property of porous medium which determines the diffusion characteristics of the medium by relating the components of pore velocity (seepage velocity) to the diffusion coefficient.

Dispersion, Hydrodynamic

Spreading of a solute through a porous medium resulting from convective transport and diffusion.

Porosity, Total

The ratio of volume of interstices in a given sample of a porous medium e.g. soil, to the gross volume of the medium, inclusive of voids. (total porosity)

Porosity, Effective

Ratio of the volume of water which can be drained from a saturated medium by gravity, to the total volume of the medium.

Recharge, Hydrogeologic

Process, natural or artificial, by which water is added from outside to the zone of saturation of a hydrogeological unit, either directly into a formation, or indirectly by way of another formation.

Specific yield (of an aquifer)

The ratio of volume of water which rock or soil, after being saturated, will yield by gravity, to the volume of given rock or soil.

Storage coefficient (of an aquifer)

Volume of water removed from (or added to) an aquifer per unit horizontal area and per unit decline (or rise) of head.

CONTENTS

1. INTRODUCTION

1.1 General Considerations

Assessment of pathways of radionuclide migration is an important consideration in the siting of Nuclear Power Plants (NPPs). In the absence of well engineered and natural barriers, the release of radionuclides from the plant or waste containment systems may contaminate ground surface and ultimately, nuclides may infiltrate into sub-surface waters and move towards water use points for human, animal and plant lives. In India, near-surface radioactive waste disposal facilities namely earth trenches, RCC trenches and tile holes, for low and intermediate level wastes are co-located at NPP site. The waste inventory in these facilities builds up during operation of the plant as well as during its decommissioning. The migration of radionuclides from the disposal facilities to far fields is possible mostly through ground water. Therefore the applicability of this guide in siting process may be very useful in generation of data required for long-term safety assessment of NPP sites and surrounding areas. The hydrogeology of a site, therefore, is evaluated thoroughly, water being the leachant of waste containment system as well as medium for migration of radionuclides. The amount of rainfall, run off, surface storage, recharge, porosity and permeability of the soil and rock formations are significant factors responsible for giving rise to different types of aquifers. The direction and rate of flow of groundwater depend on these hydrogeological attributes.

1.2 Scope

The Safety Guide deals with the following:

(i) Hydrogeological settings,

(ii) Methodologies for generation of hydrogeological database,

(iii) Methodologies for delineating groundwater regimes, and

(iv) Prediction of radionuclide migration in groundwater.

This Safety Guide deals in detail with various hydrogeological scenarios existing in Indian geological regimes and conditions and the requirement of database for assessing the characteristics of sub-surface media (Section-2). The Guide identifies minimum data to be collected and the investigative techniques and methods required for generating the database on surface and sub-surface geology at site selection stage (Section-3). The methods of monitoring a few groundwater parameters during operational and post-operational phases are described (Section-4). A brief description of the 1-D and 2-D models for different aquifer systems and their applications for prediction of radionuclide concentrations in groundwater as a function of space and time have been included (Section-5).

The effect of groundwater conditions on the foundations of power plant and other civil structures has not been included in the Guide as this aspect is dealt separately in another Safety Guide [1].

2. GEOHYDROLOGICAL CONSIDERATIONS

2.1 Geological Considerations

Geohydrology of an area is directly related to the geology of sub-surface formations, its characteristics and structures. The soil cover, weathering, consolidation, nature and structure of mineral orientation, porosity, alignment and density of joints, fractures, faults, folds, shear zones, lineaments etc. affect groundwater potentiality and flow pattern. Safety Code on "Siting of NPPs" [2] and Safety Guide on "Seismic Studies and Design Basis Ground Motion"[3] give the seismic and geological factors to be considered viz. data on tectonic features; faults and lineaments, surface collapse and subsidence or uplift and soil liquefaction. In general, three types of geological set-ups exist:

(i) unconsolidated/consolidated thick sediment cover, the bed rock being at great depths,

(ii) thin soil cover followed by porous rock viz., sandstone, shale, schists etc, and

(iii) thin soil cover followed by non-porous, impervious crystalline rocks viz. basalt, granite, gneiss etc.

The geological and soil maps of India show the various set-ups as above in Figs. 2.1 and 2.2.

2.2 Geohydrological Scenarios

Availability of groundwater, its extent and flow pattern depend mainly on porosity and permeability of the substrata, hydraulic gradient and surface hydrological features. Porous media of sand and clay normally contain a lot of water and the flow depends on intergranular connections and permeability. The effective porosity plays an important role in groundwater hydrology. In hard rock formations, weathering, mineral lineations, layering, dip, joint pattern, fracture density, fault planes etc. are features responsible for formation of aquifers. In all the cases, an impervious layer has to be there at the bottom so that groundwater forms an aquifer. There are five main scenarios of aquifers based on lithological set-ups in which they occur. They may be unconfined or semi-confined/leaky or confined (Figs. 2.3(a) to 2.3(e)).

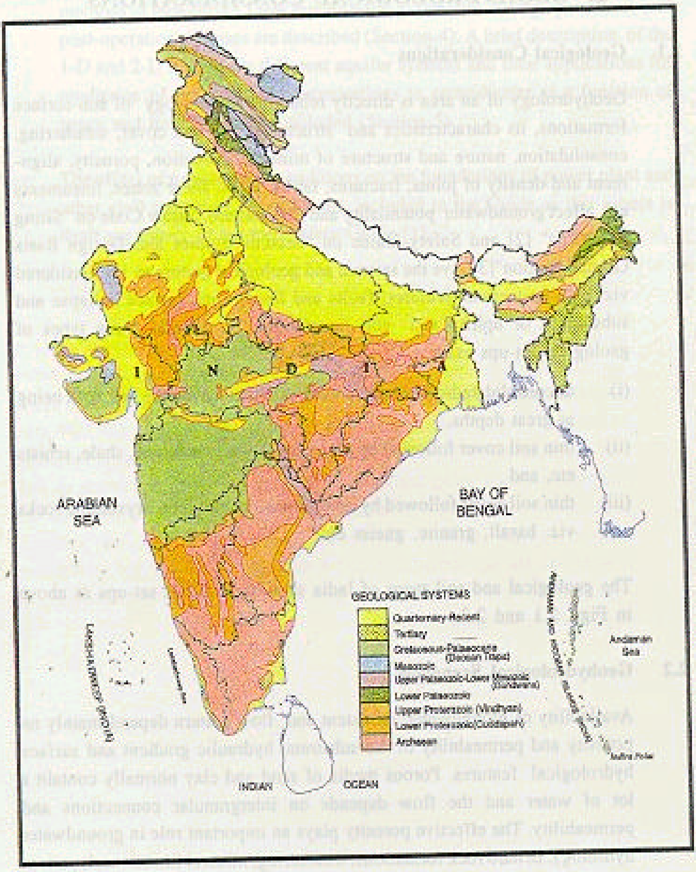

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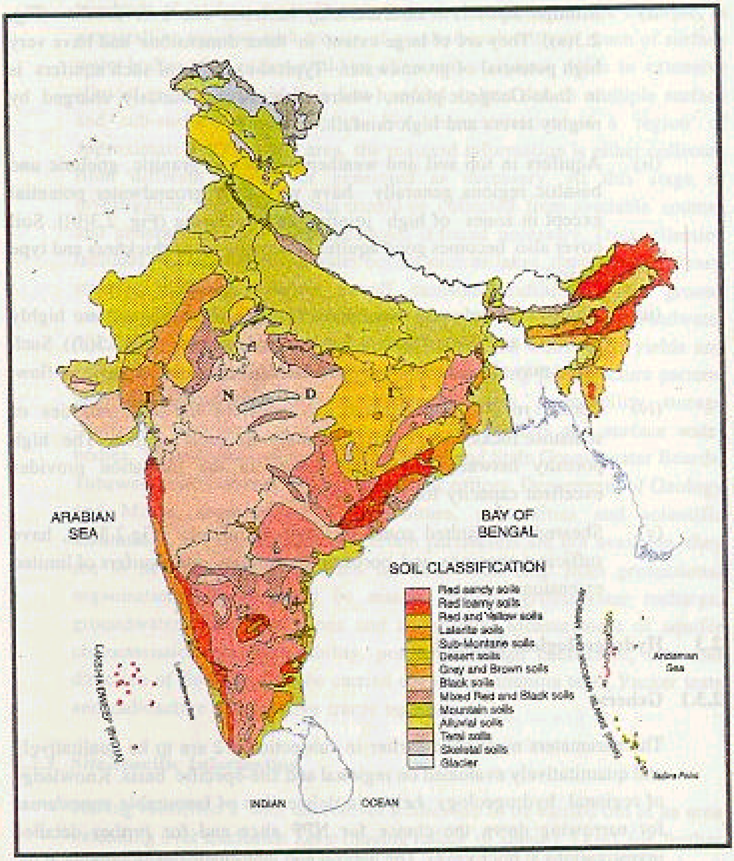
Fig. 2.1 GEOLOGICAL MAP OF INDIA



Based upon Survey of India map outline printed in 1994 with the permission of Surveyor General of India.

The external boundaries and coast lines of India agree with the record/master copy certified by Survey of India. The information given in this map is to indicate soil distribution in India for scientific purpose and not for any other purpose.

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Fig. 2.2 SOIL MAP OF INDIA

(i) Multiple aquifers of sand and clay horizons one over another (Fig. 2.3(a)). They are of large extent in three dimensions and have very high potential of groundwater. Typical example of such aquifers is in Indo-Gangetic plains, where they are continuously charged by mighty rivers and high rainfall.

(ii) Aquifers in top soil and weathered zones in granitic, gneissic and basaltic regions generally have very little groundwater potential except in zones of high jointing and fracturing (Fig. 2.3(b)). Soil cover also becomes good aquifer depending on its thickness and type of soil.

(iii) Aquifers in hard rocks which have very thin soil cover and are highly fractured and jointed up to a few hundred meters, (Fig.2.3(c)). Such zones may also have good groundwater potential and significant flow.

(iv) Porous rocks like sandstone and limestone and some varieties of schistose rocks, (Fig.2.3(d)), normally are good aquifers. The high porosity between grains and layers in the formation provides excellent capacity for water storage.

(v) Sheared and faulted zones of rock formations (Fig.2.3(e)), have sufficient openings and porosity for formation of aquifers of limited extensions.

2.3 Hydrogeological Evaluation

2.3.1 General

The parameters mentioned earlier in subsection 2.2 are to be qualitatively and quantitatively evaluated on regional and site-specific basis. Knowledge of regional hydrogeology helps in delineation of favourable zones/areas for narrowing down the choice for NPP sites and for further detailed investigations at microlevel. The natural and man-made developments at the site may also influence site hydrogeology .

2.3.2 Regional information

A 'Region', in hydrogeological sense, can be explained as an area which may have to be evaluated for gaining a reasonably good understanding of the surface hydrological and sub-surface geohydrological features for ensuring long-term safety of the facility to be constructed and the surrounding environment. The extent of the region may vary from a few tens to a few hundreds of sq.kms depending on general characteristics. For example, in a crystalline massive rock terrain of granite/basalt without much of surface water bodies, the region could be a few tens of sq.kms, while in extensive alluvial regions it could be a few hundred sq.kms due to multiple surface and sub-surface water systems. For characterisation of a 'region' of approximately 100 sq.km. area, the required information is either collected from different sources or generated as necessary. At this stage of investigation, macro-level data should be collected from available sources and generated at a few select locations, if found necessary. Data collection includes rainfall, details of water bodies such as lakes, dams, ponds, rivers, streams, evapotranspiration, runoff, rainwater infiltration into ground (recharge), water table fluctuations, groundwater quality, groundwater discharge points, presence of open wells and tube wells, their yields and recuperation rates, sub-surface geology and layering-joint-fracture pattern, aquifer characteristics such as thickness, extent, permeability, storage coefficient and their relationship with other aquifers and surface water bodies. The data are collected from Central and State Groundwater Boards, Tubewell organisations, District and Block offices, Department of Geology and Mines, Department of Agriculture, universities and scientific institutions. If complete data on certain parameters are not available, they are to be generated at selected locations with help from professional organisations. These could be mainly run-off, groundwater recharge, groundwater table fluctuations and contouring. Measurement of aquifer characteristics like permeability, porosity, storage coefficient, rate and direction of flow etc. can be carried out using pumping tests, Packer tests and radioactive and inactive tracer techniques.

2.3.3 Site-specific Information

Having identified a site, microlevel studies are to be carried out in an area extending over Exclusion Zone (having radius of about 1.5 km) for further detailed information. The hydrogeological parameters to be determined are:

(i) the depth of water table and its fluctuations,

(ii) the rate of flow of groundwater and dispersivity,

(iii) thickness of the aquifer,

(iv) groundwater discharge or extraction points and the quantum of water used,

(v) geochemistry of groundwater and its influence on the interaction of radionuclides with soil or rock (Refer section 4.3), and

(vi) soil and rock mass characteristics.

The Code of Practice on Safety in NPP Siting [2] does not identify any rejection criteria with respect to hydrogeology. It mentions that it is preferable to have groundwater table depth of at least 2.0 m below the grade level. Desirable characteristics from hydrogeological considerations are generally as follows :

- very thin aquifer (a few meters) which does not have any connection with other aquifers;
- deep groundwater table with very low flow (< 1mm/day);
- no significant fluctuation of groundwater table; and
- sub-surface geology should be of hard extensive homogeneous formation having low porosity and permeability, but with minerals of high sorption property.

At the stage of site-specific investigation, data generation becomes the overriding factor than data collection. Normally, in a limited area of 1.5 km radius (exclusion zone), geological mapping, geophysical surveys, drilling of boreholes, borehole loggings and sample testing are done for detailed evaluation of the area. Borehole investigations precisely provide information on aquifer characteristics such as extent, thickness, porosity, permeability, hydraulic gradient, storage coefficient, groundwater level fluctuation, rate and direction of flow. Hydrogeological set-up of the site is to be observed for at least a period of one year covering all seasons, before the construction of NPP commences. All seasonal variations in the set-up should be studied and data interpreted for hydrogeological characterisation of the site. The data on groundwater movement along with geochemistry of soil and rock could then be used for radionuclide migration modelling and verification.

FIG. 2.3(a) SCENARIO - 1 AQUIFER IN SAND AND CLA Y LAYERS

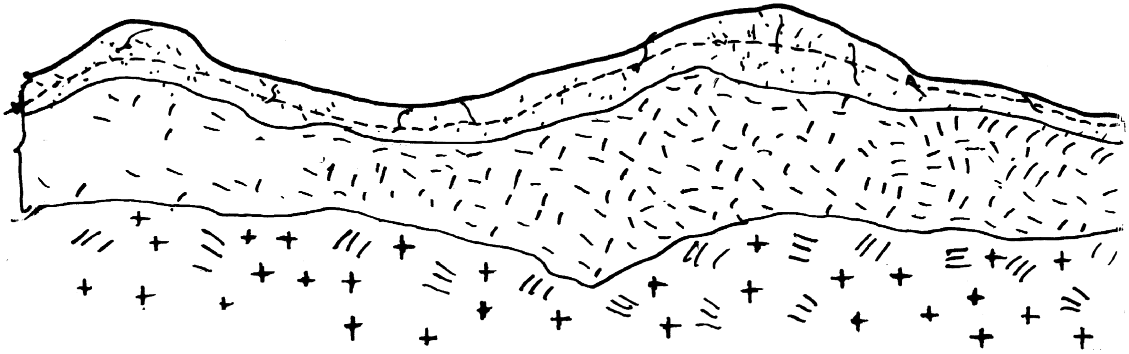


Fig. 2.3(b) SCENARIO - 2 AQUIFER IN SOIL AND WEA THERED ROCKS

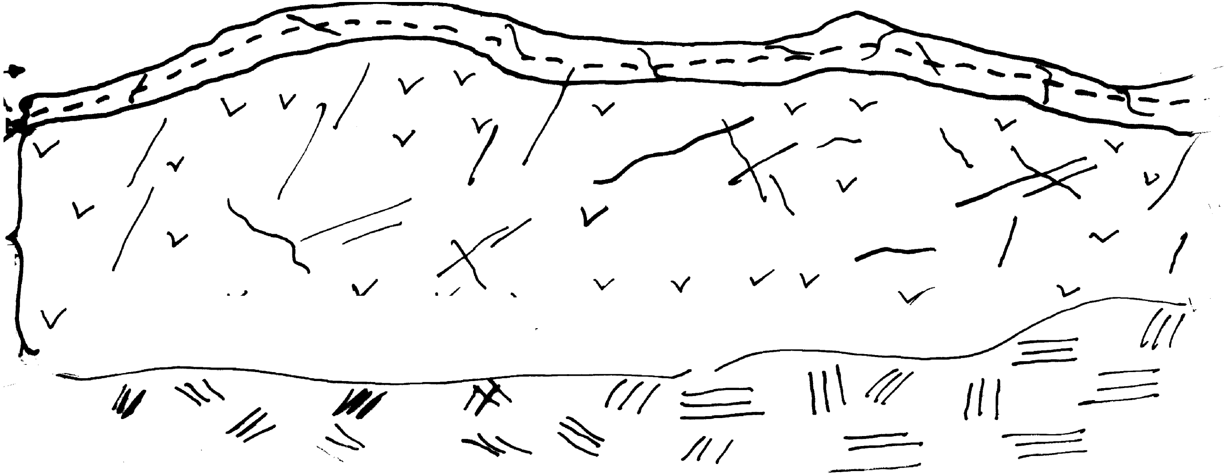


Fig. 2.3(c) SCENARIO - 3 AQUIFER IN SOIL COVER AND JOINTED ROCK

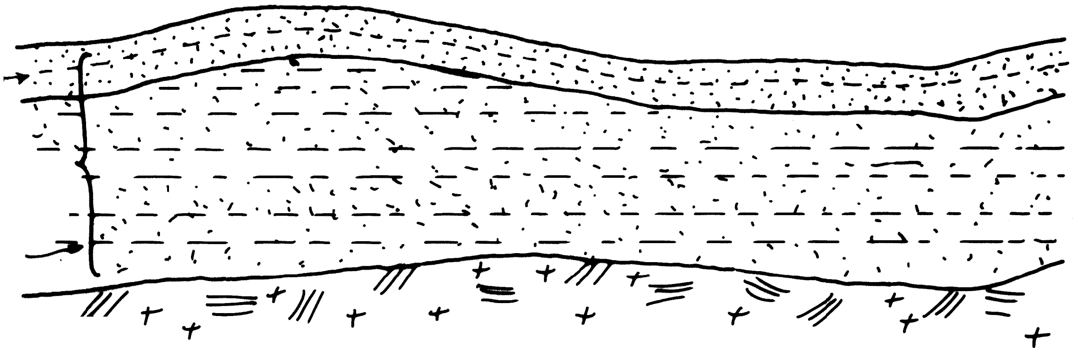


Fig. 2.3(d) SCENARIO - 4 AQUIFER IN GRANULAR AND SCHIST OSE ROCKS

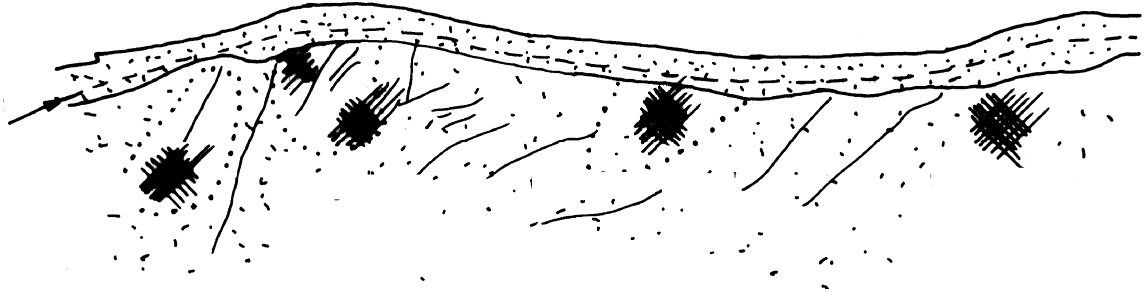


Fig. 2.3(e) SCENARIO - 5 AQUIFER IN SHEARED AND FRACTURED ZONES

3. INVESTIGATIONS AND DATA COLLECTION

3.1 General

The investigations for selection of sites for NPP, from hydrogeological considerations are carried out in two stages, i.e., regional area investigations on macrolevel and site-specific investigations on microlevel. The process of investigation commences with data/information collection on a regional level and ends at the generation of data/information and its interpretation for a specific site.

3.2 Regional Hydrogeological Investigations

For hydrogeological assessment at regional level, data collection on a number of major hydrological and hydrogeological parameters is undertaken. Data collection is based on maps, reports and statistics available with concerned organisations. On a regional level, data on the following parameters are collected:

(i) rainfall,
(ii) run-off,
(iii) surface water bodies,
(iv) recharge,
(v) uptake/usage.

Average annual rainfall and run-off data for the region are required. A typical format for rainfall data is shown in Annexure-I. Fig. 3.1 shows the general trend of annual rainfall in India.

All water bodies, namely tanks, rivers, dams, lakes, waterfalls and canals plotted on 1:50,000 or appropriate scale on a map for the region should be available.

If available, data on annual rate and quantum of recharge into the ground and seasonal groundwater contour maps may be collected to determine the replenishment of water in the aquifer. The groundwater contour map enables determination of the gradient in hydraulic head of the aquifer.

Discharge points like streams, lakes, dams and groundwater user points like significant springs, wells etc. should be identified on the hydrogeological map of the region. Information on physical and structural nature of geological rock formations, their type, and degree of weathering should be collected to know the permeability of the formation, groundwater retention and flow characteristics.

Data on major aquifers such as type, size and shape, permeability, transmissivity and storage coefficient should be collected.

Actual field surveys should be carried out on regional basis to confirm the surface and subsurface hydrological features shown on the large-scale regional hydrological and hydrogeological maps. This is a field check, because in course of time rivers may change their routes, wells dry up and the extent of surface water bodies reduce, enlarge or shift.

The regional data collection and investigations are aimed at characterising surface and subsurface hydrology of the region in a qualitative manner to arrive at a technical assessment of the region on this count.

3.3 Site-specific Hydrogeological Investigations

3.3.1 General

At site selection stage, data available at the nearby Meteorological Station or from investigations carried out by agencies like Central Ground Water Board, Geological Survey of India etc. in the area should be collected. This is to be followed by site-specific investigations given below, before the facility goes into operation. The observations in the initial stages may be for a minimum period of one year as given in the Code [2].

3.3.2 Surface Systems

3.3.2.1 Rainfall

Rainfall is the major source for groundwater to predict aquifer characteristics/behaviour and to calculate recharge to ground. Rainfall data for at least three years should be collected at the site using rain gauge. The data should be specific on the amount and intensity of rainfall on daily, monthly and annual basis along with peak values. Annexures-II and II-A show monthly and year-wise maximum daily rainfall, respectively at Trombay for year 1959-1997. Similarly, Annexure III gives monthly rainfall for

1961-1995 and Annexure III-A gives daily average rainfall for 1961-1994 at Tarapur.

3.3.2.2 Run-off

Rainwater falling on ground surface goes to make the top surface saturated, apart from flowing towards lower levels through natural drainages as run-off. Run-off, which is mainly responsible for formation of surface water bodies, should be estimated through stream gauging. Knowledge of this parameter is important as surface reservoirs may play a major role in recharge of aquifer and ultimately to groundwater movement.

3.3.3 Recharge/Infiltration and Discharge

Rainwater when comes into contact with earth's surface gets distributed in three ways, namely infiltration into the ground, flow on surface of lower elevation as run-off and return to atmosphere by evaporation. The hydrological cycle is shown in Fig.3.2. Groundwater recharge is known by determination of quantity and rate of downward movement of water into soil using tracer techniques. The movement in unsaturated zone could be found out by injecting tritiated water at plant root level at an approximate depth of 70 cm, before the onset of monsoon and drawal of soil samples by hand augers for analysis and evaluation of migration rate in vertical and horizontal directions. This gives the annual rate of recharge of rainwater into the ground. The downward moving water ultimately reaches the saturated zone to recharge the aquifer.

The surface water flows from permanent and intermittent sources such as waterfalls, impoundments, lakes and ponds should be identified, along with the identification of major water sources in the vicinity of site, which will influence the hydrology over an area of 1.5 km radius around the site. Similarly, discharge of underground aquifer in the form of open wells, tubewells and springs in the area should be evaluated for the rate and quantity of flow, flow pathways and water withdrawal rate using standard methods of tracer tests and pumping tests, described later in Section 3.3.6.10 to assess the safety of plant site upto 1.5 km. radius and public at large around it.

3.3.4 Groundwater Table Fluctuations

In order to study the fluctuation in water table during the year, groundwater table contour map of the site should be prepared based on available data for a minimum period of 3 years. The preliminary exploratory boreholes drilled at the site could be used for this purpose. The highest and lowest water table of the area is important as migration of radionuclides depends on the contact of groundwater with containment systems having radioactive materials and waste. If the rise of water table is significant, it may also create waterlogging and flooding of the area. This can be known by drilling a few boreholes in the area and measuring water levels in them over a period of time as mentioned above. These observations combined with expert judgement will help in arriving at design basis. The boreholes may afterwards serve as monitoring wells for detection and estimation of movement of radioactivity.

3.3.5 Geological Setup

Detailed geological mapping of the site is to be carried out which includes the following :

Surface Features

- lithological units including soil profiles and their sequences,
- dip, strike, lineations, foliations,
- presence of faults, fracture and joint pattern, and
- weathering pattern.

Sub-surface Features

- zones of soil, weathered rock and fresh rock,
- structural features such as dip, strike, joints, fractures, faults etc.,
- petrographical and mineralogical composition, and
- lithological and structural characterisation from borehole data.

Geological map for the area on a scale of 1:1000 or as appropriate should be prepared and interpreted. Geological logs of boreholes and various sections through them on appropriate scale must be prepared. The depth of boreholes should extend upto a depth of about 30m below grade level. The number of boreholes should be adequate to arrive at a geological profile of site area. Boreholes drilled for other purposes at the site, such as for foundation, can also be used for this purpose.

3.3.6 Aquifer Characteristics and Parameters

3.3.6.1 General

Characterisation of aquifers at NPP site is important. Hydrological assessment and information on groundwater flow pattern can be obtained through the study of following parameters:

(i) Thickness

Boreholes of about 30m depth generally provide information of the shallow aquifer thickness, which is important from the point of view of migration of radionuclides either from the plant site or near surface waste disposal facilities. Information on entire thickness of deep aquifers should be collected from deep boreholes drilled earlier in and around the site for other purposes by Groundwater Resource Development Agencies, otherwise it may be generated. Depth upto which boreholes may have to be drilled is to be decided case by case.

(ii) Extent

The information on three-dimensional extent of aquifer could be obtained from available logs of deep boreholes drilled earlier in the area. Shallow boreholes of about 30m depth drilled on grid pattern could provide horizontal extent of top aquifers and their hydrogeological variations. Grid interval is decided on the variation of lithological units as shown by surface geological mapping, pitting and trenching. The correlation of boreholes will give a clear picture of the number of aquifers, size, shape, and extent.

(iii) Porosity

Porosity values are obtained by laboratory tests on collected samples while in-situ measurements can be made through geophysical techniques viz., sonic, neutron, resistivity, and gamma-gamma logging.

(iv) Permeability [4]

Field permeability of porous media is determined by pumping tests in boreholes or using tracer techniques. In a fractured rock, permeability is determined by injecting water at variable pressures between two packers (rubber seals) in the borehole and measuring the rate of water flow into the rock. This is calculated using equation I-1 of Appendix-I.

(v) Transmissivity

This is the rate of flow of groundwater through a unit width of aquifer under a unit hydraulic gradient. It is the product of permeability and thickness of the aquifer. Transmissivity is determined by conducting pumping tests in the borehole and is calculated using Theis equation (II.5) of equilibrium and graphical method for a confined aquifers as given in Appendix-II [5a].

(vi) Storage Coefficient

Storage coefficient is represented as the net volume of water released from or absorbed per unit surface area of the aquifer per unit change of head normal to the surface. This is also determined by pumping tests in boreholes and is calculated using Theis equation and graphical solution for confined aquifers. Mathematical representation is shown in Appendix-II [5a].

(vii) Hydraulic Gradient

Hydraulic gradient, i, is the change of hydraulic head, dh, with the length of the porous medium column, dl, through which water flows. This can be determined by noting the difference between water heads in two wells divided by the distance between the wells. It is represented as $i = dh/dl$.

(viii) Specific Yield

It is the ratio of volume of water that can be drained after saturation (under gravity) to the volume of aquifer. It is generally expressed in percentage.

(ix) Direction and Flow of Groundwater

The rate and direction of flow of groundwater should be determined by tracer techniques using both radioactive and inactive tracers. For this purpose, both single and multiple bore wells can be employed.

Tritiated water or other radioisotopes viz. Iodine-131, Bromine-82 and inactive tracer like Rhodamine-B dye are tracers generally used in these studies as per methods given below:

(a) Single Well Dilution Method [6]

Filtration velocity in an aquifer is measured under natural or induced hydraulic gradient. The velocity is calculated from Darcy's formula. Tracer is injected in the borehole and the variation in concentration of the tracer is determined at regular time intervals. The computation of filtration velocity by this method is given in Appendix-III.

(b) Multi-Well Method

In multi-well system, tracer is injected and thoroughly mixed in the central well of a circular array of boreholes. The peripheral boreholes are located at equal radial distances. The tracer moves with groundwater in the normal direction of flow and is detected by scintillation probes installed in the peripheral observation boreholes or in water samples collected at regular periodicity. The direction of borehole where the tracer is first detected is the direction of flow of groundwater with respect to the central borehole. The time taken by tracer to move the distance between central well and borehole of detection gives the rate of movement of groundwater. Such experiments are to be conducted during monsoon, pre-monsoon and post-monsoon periods to obtain data on maximum flow rate in the year.

(x) Interconnection with other Aquifers

It is important to know about interconnections in multi-aquifer system in an area. The borehole geology and the results of borehole tests conducted both by extent and area generally indicate the interconnections, if any, amongst different aquifers. It will also show the relative behaviour of aquifer with respect to their charging or yielding. This information is of significance in multi-aquifer system, because the hydraulic property of one aquifer affects the flow pattern of another.

(xi) Determination of Distribution Coefficient (K_d)

Soil and rock media have sorption characteristics for ionic substances. The phenomenon is mainly classified as (a) adsorption, (b) absorption and (c) ion exchange. Adsorption is a surface phenomenon by which isotopes are attached to the surface of a particle due to electrical charges. Absorption takes place due to entrapping of ions/colloids between the grains of the material. In the case of ion exchange, the non-radioactive ions are exchanged with radioactive ions of the same group of the periodic table of the elements. The property of sorption of the medium thus helps in arresting radionuclides within the medium and does not permit all radionuclides to migrate from the point of release in groundwater upto the point of discharge or use. Every medium has different degree of sorption. The clayey material has better sorption than sandy material. The minerals present in soil/rock also play an important role in arresting the radionuclides by ion exchange. Distribution coefficient (K_d) is the ratio of uptake of nuclide into the solid to the nuclides remaining in the solution at equilibrium. K_d is an important parameter and is determined in the laboratory by either static or dynamic method (batch or column). In batch test a known amount of powder of specific mesh size is mixed with a known solution of radionuclides and kept in contact or stirred for a fixed period of time. The solution is centrifuged and filtered and the concentration of radionuclide is determined by standard methods[3]. The difference in concentration of radionuclide in the solution before and after contact with the powder is the uptake by the solid. Distribution coefficient is then calculated. Field measurements are difficult and hence generally laboratory values of K_d are used in calculations. Typical values of K_d (l/kg) for some of the rocks and soils for Sr-90 and Cs-137 are given below [7]:

Materials and Conditions	K_d (l/kg)	
	Strontium (Sr)	Cesium (Cs)
Basalt, 32-80 mesh	16-135	792-9520
Basalt, 0.5-4 mm, 300 ppm TDS	220-1220	39-280
Sand, Quartz- pH 7.7	1.7-3.8	22-314
Sands	13-43	100
Carbonate, > 4 mm	0.19	13.5
Soils	19-282	189-1053
Shaley, siltstone > 4 mm	8	309
Alluvium, 0.5-4 mm	48-2454	121-3165

3.4 Methodology of Investigations

3.4.1 Surface Geophysical Surveys

Geophysical surveys at the site on a close grid pattern reveal lot of information regarding sub-surface inhomogeneities up to the required depth like variation in lithology, presence of joint and fracture zones and aquifer zones. This in turn gives an idea to decide and optimize the number of bore holes to be drilled and their locations. Although there are number of geophysical surveys viz. magnetic, electrical, resistivity, electromagnetic, gravity, seismic, self potential and induced polarisation, which could be carried out to get maximum information, only a few of them have to be chosen based on the site characteristics. For hydrogeological information, the proven methods of geophysical surveys are mainly resistivity and low velocity seismic methods.

3.4.1.1 Resistivity Method

The method uses change in electrical resistivity in the ground due to variation in lithology, water content and mineralogical properties. The survey is conducted by portable equipment and is most economical. The most common method is to measure differences in electrical potential induced by applying an external electric current between two electrodes in the form of a standard array[8]. The distance between the current electrodes determines the depth of formation under investigation. In a uniform porous formation resistivity depends on water content and the type of soil/rock media. The resistivity survey, thus, provides the depth and thickness of the water column. This method in certain cases can also detect the salinity of water and its interfacing with fresh water.

3.4.1.2 Seismic Method

Using low seismic velocity method for shallow depths, reflection seismics have been used to determine the depth of bed rock, distribution of buried channels, faulted zones and the pervious and impervious zones with their thicknesses. This investigation can provide very clear picture of the number, nature and type of aquifers at a site [8].

3.4.2 Borehole Drilling

This is the only direct method to have a complete knowledge of the sub-strata. Continuous core samples recovered from boreholes show exactly the nature of rock, type and their structural characteristics. Through boreholes, aquifers are identified, their correlation with each other known and groundwater flow pattern quantified through additional tests. As such, a number of boreholes consistent with general geohydrology of the site, to the required depth should be drilled at the site including solid waste disposal area. Boreholes are used first to characterise the sub-surface hydrogeology and latter for monitoring the behaviour of migration of radionuclides through groundwater.

3.4.3 Borehole Geological Logging

The borehole geological logging of core samples as mentioned earlier give information about subsurface rock features and associated hydrology.

3.4.4 Borehole Geophysical Logging[8,9]

Borehole geophysical loggings are of many types, but the significant ones related to revelation of hydrogeology are as follows. A number of geophysical loggings are mentioned below, but one or more combinations thereof can be used to find out various parameters like porosity, permeability, salt content etc.

(i) Electrical Resistivity Log

A multi-electrode probe in which electric current passes between two electrodes via the surrounding rock measures the electrical conductivity or resistance. With this logging technique, correlation of aquifer, depth of water table, water content in the formation, porosity of aquifer and salt content of water can be determined.

(ii) Caliper Log

This log is used to identify fractures in borehole drilled in rock formation, indicating possibility of the presence of aquifer zones in hard strata.

(iii) Neutron and Gamma-Gamma Logs

Neutron log measures the thermal neutron flux or induced gamma radiation flux resulting from neutron emitting source in a probe. The reduction in neutron velocity in the formation depends on the presence of hydrogen or water content. This log provides moisture content in unsaturated zones and porosity in saturated zones. Gamma-Gamma log records the intensity of induced gamma radiations emitted by an artificial source and back-scattered after attenuation in the surrounding formation. It is used to identify lithology and to measure bulk density and porosity.

(iv) Gamma Log

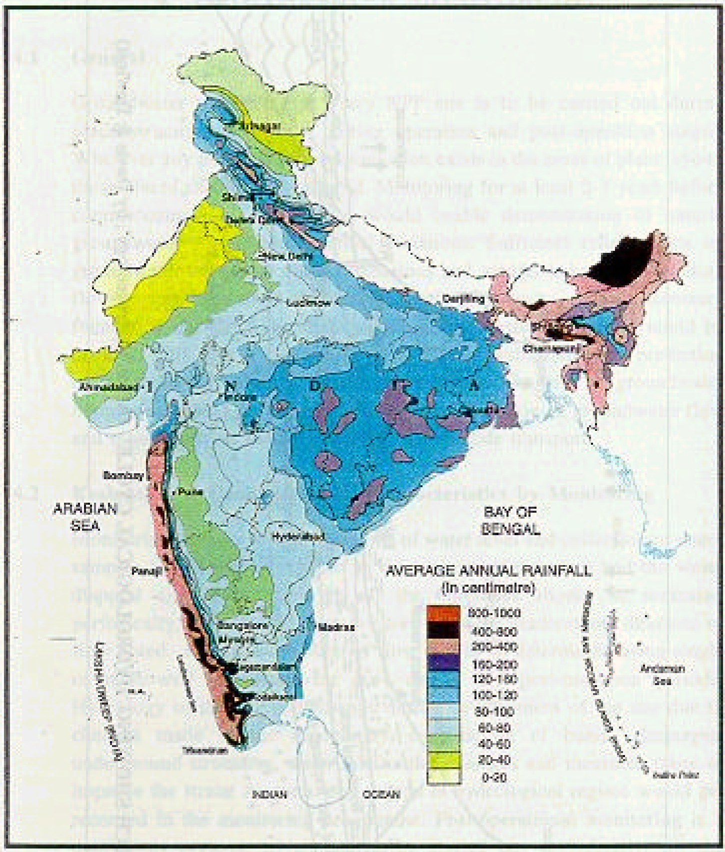
Gamma log measures natural gamma radiation emitted by rock formation. In hydrogeological context, it delineates mainly the presence of clay or shale content or an aquiclude.

(v) Sonic/Acoustic Log

Sonic log measures the time taken by a particular sonic wave to travel a known thickness of formation and provides porosity of strata and identifies fractures and fissures, which may hold water and influence its movement within or outside the formation.

3.4.5 Tracer Techniques for Groundwater Movement

This aspect has already been discussed in detail in Section 3.3.6.10.



Based upon Survey of India map outline printed in 1994 with the permission of Surveyor General of India.

The external boundaries and coast lines of India agree with the record/master copy certified by Survey of India. The information given in this map is to indicate Annual Rainfall of India for scientific purpose and not for any other purpose.

The internal details were designed and cartographed by 'TTK Pharma Limited - Printing Division, Chennai - 600 044. Phone Number 236 8824 and copy right 1987.

Fig. 3.1 ANNUAL RAINFALL MAP OF INDIA

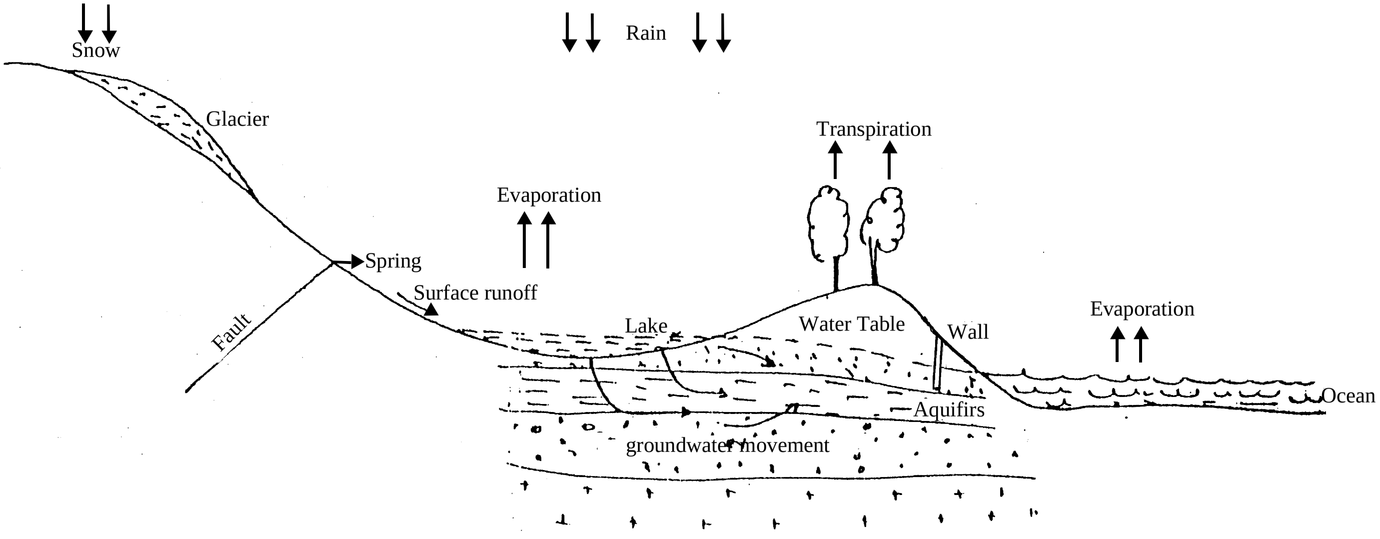


Fig. 3.2 Sketch showing 'hydrological cycle' (After 'Hydrology' by Davis & Dewiest)

4. GROUNDWATER MONITORING

4.1 General

Groundwater monitoring at every NPP site is to be carried out during preconstruction, as well as during operation and post-operation stages. Wherever any potential for contamination exists in the areas of plant layout, those places should be monitored. Monitoring for at least 2-3 years before commencement of construction would enable determination of natural groundwater regime and seasonal variations. Sufficient reliable data on groundwater system in three dimensions and aquifer behaviour including flow pattern should be available through such study, so that necessary foundation design of the shallow radioactive waste repositories could be decided. This data is also useful for providing information on prediction of migration of radionuclides in groundwater. The aim of groundwater monitoring should be for preparation of three-dimensional groundwater flow and mass transport model including radionuclide transport.

4.2 Evaluation of Geohydrological Characteristics by Monitoring

Monitoring consists of measurements of water level and collection of water samples from boreholes drilled in the vicinity of the plant and the waste disposal site. Water table in all the boreholes should be measured periodically, and seasonal contours drawn and the gradient and direction of flow noted. Rate and direction of flow should be determined using single or multi-well techniques for pre-, during and post-monsoon periods. Hydrology of the site may change during development of the site due to changes made in the topography, construction of bunds, drainages, underground structures, water inlet-outlet passages and measures taken to improve the strata. As such, any change in hydrological regime would get recorded in the monitoring programme. Post-operational monitoring is a continuous process, which has to be carried out periodically, till the termination of institutional control of the site. Periodicity of monitoring will, however reduce as a function of time. After closure of the facility and upto the termination of institutional control, monitoring can be reduced to twice a year, pre- and post-monsoon periods.

4.3 Geochemical and Radiochemical Analysis of Water

Some of the important parameters need to be analysed during pre-operational stage are:

- temperature,
- pH value,
- Eh (Redox potential) value,
- electrical conductivity,
- total solids,
- total dissolved solids,
- dissolved oxygen,
- chloride,
- fluoride,
- nitrate,
- sulphate,
- dissolved iron,
- trace elements,
- K_d of aquifer medium for radionuclides of relevance, and
- background radionuclide concentration.

During post-operational phase, the concentration of different radionuclides is to be determined periodically along with the parameters mentioned above. This will determine the quality of water for potability.

Annexure-IV gives the methods and measurement frequencies for monitoring programme at Nuclear Power Plants.

5. MODELLING

5.1 General

Migration of radionuclides after release, if any, from Nuclear Power Plants or waste disposal facilities depends mainly on the physicochemical properties of rock, soil and groundwater flow pattern. As such, modelling of flow of groundwater and retention of radionuclides by the medium during its movement in flowpath enables prediction of concentration of radionuclide at a particular distance from the point of release and consequent potential radiation doses.

5.2 Methods of Groundwater Modelling

The purpose of groundwater modelling is to predict groundwater velocity as a function of space and time. This may be used to estimate rate of discharge of groundwater to discharge points. The simplest model of groundwater velocity would be a statement of Darcy's Law (Appendix - IV) with appropriate boundary conditions and aquifer parameters, namely, transmissivity and storage coefficient or field capacity. The model can range from a simple uni-dimensional steady state case to a highly complex transient three-dimensional case. Usually, over a long period of time, groundwater regime undergoes a change because of development and construction at a site, change in evapotranspiration and consequent rainfall pattern and other environmental conditions of groundwater flow. In case of flow in unsaturated zone, the hydraulic conductivity/permeability (K) is a function of the degree of saturation i.e., volumetric moisture content, apart from spatial distribution, as under:

$$K = K(x,y,z,\phi)$$

where ϕ is the volumetric moisture content and x, y, z are the co-ordinates in three dimensions. These functional relations in 1-D and 3-D for isotropic and anisotropic cases of hydraulic conductivity are available in literature[8].

One of the aquifer systems commonly encountered is a single confined aquifer. Eq. V.3 in Appendix-V describes groundwater flow through a single confined aquifer in three dimensions. Flow through fractures in a hard rock medium is modelled as a set of a parallel plates and is described by equation V.9 in Appendix-V. Appendix-VI gives necessary parameters for groundwater flow modelling and their investigative techniques. Appendix-VII shows various parameters necessary for radionuclide migration modelling and their investigative techniques.

The methods of solution are categorised as:

(i) analytical,

(ii) semi-analytical, and

(iii) numerical techniques, such as finite difference method and finite element method.

These analytical solutions can be used for simple cases and for giving insight into the problem. For more complicated cases, finite difference or finite element method is to be followed.

5.3 Radionuclide Migration Modelling

5.3.1 Governing Processes

This section describes the behaviour of radioactive materials in groundwater and models for assessing radionuclide movement in aquifers of different types. The movement of radionuclide in aquifer is controlled by:

- groundwater flow (transport),
- spread of contaminant front (hydrodynamic dispersion), and
- retention and release of radionuclides from solid phases (interphase distribution).

The concentration of radionuclides at the nearest point in the region where the water is extracted for use and the time needed for radionuclide to reach this point are two essential pieces of information required from models for assessing the evaluation of impact.

5.3.2 Description of Models

This sub-section describes some of the modelling approaches that can be used to compute spatial and temporal distribution of radionuclides in groundwater. If the groundwater velocity and path length are known, the travel time of groundwater and radionuclides from the source of release to the point of water use can be estimated. Reduction in radionuclide concentration between the release point and the point of water extraction for use can be determined by solving the hydrodynamic equation representing transport, dispersion, sorption-desorption processes and radioactive decay. Choice of the model depends on:

- selection of source term for release which takes into account specific characteristics relating to the integrity of the waste form;
- applying a realistic model for transport, dispersion and sorption-desorption of radionuclides as determined by site characteristics; and
- consideration of actual distance from release region to the point of water extraction for use. Any model needs to be evaluated prior to its application. In literature many models of varying complexity are described for computing spatial and temporal distribution of radionuclides in groundwater. Some suitable models from experience gained at different NPP sites are summarised in Appendix-VIII.

5.3.2.1 Transport parameter

The velocity of groundwater can be determined by tracer techniques described in Section 3.3.6.10. Low groundwater velocity in aquifer is desirable for retardation of migration of radionuclides. Groundwater velocity can be utilised to evaluate the travel time of radionuclides between the site and the point of extraction of water for use. However, this will require information on distribution coefficient (K_d) for a given radionuclide.

5.3.2.2 Hydrodynamic Dispersion

The amount of dilution that occurs within an aquifer is fundamentally a function of hydrodynamic dispersion. The coefficient of hydrodynamic dispersion is found out from field tracer experiments to determine the transverse and longitudinal components of dispersivity. Such field experiments are time consuming, but can be speeded up by the use of a combination of injection and pumping from wells to reduce travel time. Maintaining a low injection pressure not to affect dispersion coefficient is rather difficult. Since dispersion coefficient is a function of groundwater flow, empirical relationships can be used to compute dispersion coefficient from groundwater velocity. The hydrodynamic dispersion coefficients D_x, D_y and D_z are related to groundwater velocity by the equation

$$D_x=\alpha_X U;\ D_y=\alpha_Y U \text{ and } D_z=\alpha_Z U$$

where α is the intrinsic diffusivity component in three directions. It is a function of properties of hydrogeologic materials. Its values in three directions are determined in the field using single well, two wells and multi-well tests, the range being 0.5 - 15m. for alluvial, carbonate and limestone aquifers. The range for sand and gravel varies between 2m. and 3m. However, for fractured strata, the values can be as high as 130 m.

5.3.2.3 Sorption-Desorption Processes

Sorption-desorption processes reflect the interphase distribution of soluble components of waste with solid matrix of aquifer. The effect of sorption on transport is an apparent retardation. The dispersion coefficient also gets modified due to retardation. This, coupled with radioactive decay constant, determines the concentration profile of a radionuclide. Concentration of short lived isotopes can be significantly reduced due to retardation compared to that of longlived ones.

5.3.2.4 Choice of Source Term

The basic approach to any practice of radioactive waste disposal relies on concentration and confinement of waste for an appropriate period of time under passive conditions. The objective is to ensure that constituents of waste either never reach the biosphere or reach at levels which pose even negligible risk to human health and environment. This objective is achieved by the multi-barrier concept of waste management, namely, waste form, containers, backfills and engineered safety features. The wastes are solidified into cement matrix and encased in containers of adequate integrity and stored in 3 types of disposal modules, namely unlined earth trenches, reinforced concrete trenches and steel lined tile holes. Unlined earth trenches are used only for wastes with suspect contamination, while, the other two types are generally used for radioactive wastes with significant contamination.

The model output is determined by the realism incorporated in source term. Leaching of radionuclides from waste forms due to infiltration of water would eventually pass through engineered barriers. The magnitude of leaching and breaching time of engineered barriers cannot be evaluated precisely. However, as a conservative estimate, the integrity of waste forms disposed of in earth trenches, RCC trenches and tile holes is taken to be 1, 30 and 100 years respectively.

The concentration of longlived radionuclides with half-life, say, 1000 years or more, in groundwater will not be significantly altered even if the integrity periods (expressed in years) are enhanced by a factor of 2 or 3. This can have significant effect on the concentration of shortlived radionuclides. On the other hand, the lower integrity considered will lead to higher concentrations in groundwater. The models described in Appendix-VIII consider leach rate coefficient which is the reciprocal of integrity period of the waste form.

5.3.3 Selection of Model

Simple analytical models are generally satisfactory and the need for complex models is an exception rather than rule. The assumptions inherent in simple analytical models may not be applicable for some hydrogeological systems. Complex models require collection of detailed data. Selection of appropriate release source term to be used as input for evaluation of concentration profile in groundwater is essential as it is dependent on site characteristics and the uncertainty involved in source term may offset the use of more complex models.

5.3.4 Model Evaluation

Application of models to predict spatial and temporal distribution of concentration profile of radionuclides in groundwater is subject to several sources of uncertainty. They include uncertainties associated with release source term, suitability of the model to the site itself and the validity and accuracy of the data. Only in some exceptional cases the model can be validated with field data. A sensivity analysis will be helpful in assessing the potential uncertainties resulting from the use of the model[1]. Parameters responsible for the uncertainty in model can be identified by this analysis and the value of these parameters should be evaluated with accuracy.

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[1] Refer Annexure-V for further development of the technique.

APPENDIX-I

PERMEABILITY CALCULATION

Field permeability of a formation can be determined by using standard packer test in a borehole. The rate of loss of water between the two rubber packers is noted and the permeability of that segment of rock can be calculated from equation[4].

$$K = \frac{Q}{2\pi LH} \ln\frac{L}{r} \qquad \text{.......................................} \qquad (I.1)$$

where:

K = permeability (m/sec),
Q = rate of loss of water (m^3/sec),
L = length of the segment of the borehole (m) under test (>10 r),
r = radius of borehole (m), and
H = differential head of water (m).

APPENDIX-II

THEIS METHOD [5a]

Transmissivity and storage coefficient of an aquifer are determined by pumping tests in boreholes. Water is pumped out from a borehole while the draw down is noted in another one adjacent to it. For different types of aquifers mathematical formulae [5a,10] are used for estimating these parameters. The most commonly used method (Theis method) for confined aquifers is described by the following equations:

$$s = \frac{Q}{4\pi T} W(u) \cdots\cdots\cdots (II.\ 1)$$

$$u = \frac{r^2 S}{4Tt} \cdots\cdots\cdots (II.\ 2)$$

where, W(u) is the well function of u, and

$$W(u) = -0.5772 - \log u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} + \cdots\cdots$$

$$= -Ei(-u) \cdots\cdots\cdots (II.\ 3)$$

or

$$\log s = \log W(u) + \log \frac{Q}{4\pi T} \cdots\cdots\cdots (II.\ 4)$$

$$\log \frac{r^2}{t} = \log u + \log \frac{4T}{S} \cdots\cdots\cdots (II.5)$$

where:

s = draw down (m) measured in the observation well due to constant discharge from a pumped well,

Q = discharge from pumped well (m^3/day)

T = transmittivity (m^2/day)

r = distance (m) from the pumped well to the observation well,

S = storage coefficient (dimensionless),

t = time (days) since pumping started, and

$Ei(-u)$ = exponential integral of u.

The procedure is to be followed in 4 steps:

(a) plot a log-log graph between $W(u)$ and u, known as type curve;

(b) plot a log-log graph on similar transparent graph paper between s and r^2/t, known as field curve or data curve;

Note: (If Q is constant, equations (II.1) and (II.2) show that $W(u)$ is a function of u in the same way that S is a function of r^2/t);

(c) superimpose the field curve on type curve, holding the coordinate axes of the two curves parallel and in such a way that the field curve fits best with the type curve; and

(d) choose a common point (match point) arbitrarily on the overlapping part of the graphs. Read the match point co-ordinates u, $W(u)$, r^2/t and S. T and S can be calculated now by putting match point co-ordinates in equations II.1 and II.2. The following figure Fig II.1 shows the typical match curves.

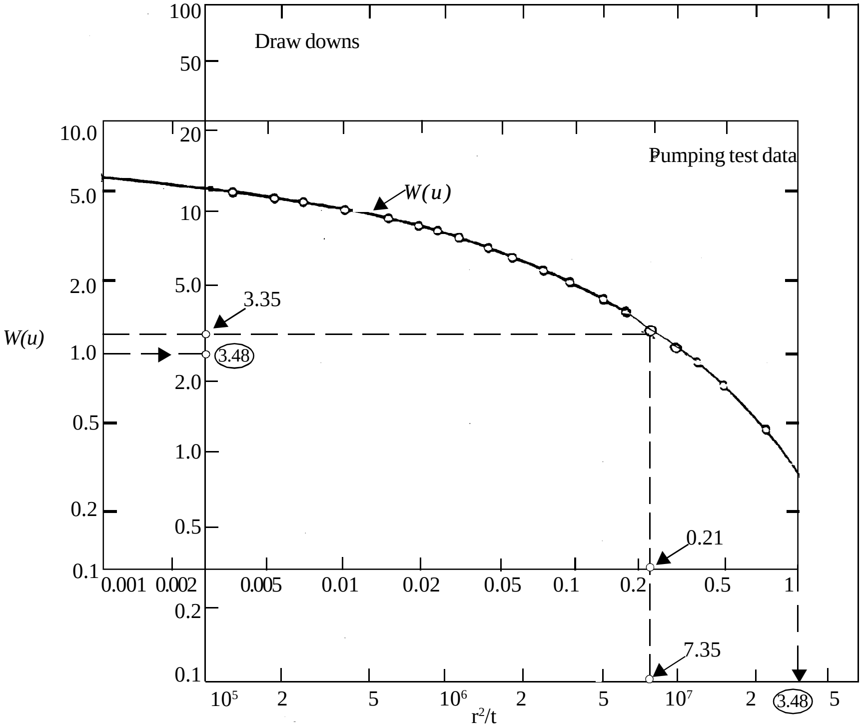

Fig. II.1 CURVE SHOWN ABOVE IS THE RESULTANT OF SUPERIMPOSING TYPE CURVE OVER DATA CURVE. (Incidentally, here all the points of both the curves are matching)

APPENDIX-III

CALCULATION OF FILTRATION VELOCITY

Single well dilution technique is used in borehole, where tracer is thoroughly mixed with groundwater and tracer concentration is measured continuously. Filtration velocity U_f (m/sec) of groundwater can be calculated as under [6]

$$U_f = -\frac{V}{\alpha F t} \ln \frac{C}{C_0} \qquad \text{.. (IV. 1)}$$

where:

V = volume of water in which dilution has taken place (m^3),

F = cross section of the measuring volume perpendicular to the direction of groundwater flow (m^2),

t = time taken for tracer concentration to reduce from C_0 to C (sec),

α = correction factor accounting for distortion of flow lines due to the borehole (Q_b/Q_f),

Q_b = horizontal flow rate in borehole (m^3/sec),

Q_f = flow rate in the same cross-section of formation (m^3/sec).

APPENDIX-IV

DARCY'S LAW [5b]

$$Q = -K.A.\frac{dh}{dl} \qquad \text{..(III. 1)}$$

where:

Q = flow rate (m^3/sec),

K = coefficient of permeability (m/sec),

A = cross sectional area of flow of groundwater (m^2), and

$\frac{dh}{dl}$ = hydraulic gradient.

Negative value indicates that flow is taking place in the direction of decreasing head.

APPENDIX-V

GROUNDWATER FLOW THROUGH POROUS MEDIUM [5C]

The basic equation for groundwater flow is given as

$$\left[\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}\right] = [\rho(1-n)\alpha+n\beta]\,\frac{\partial p}{\partial t} \quad \text{....................(V.1)}$$

where:

ρ = density of ground water

u = Vx(x,y,z,t) = ground water velocity component in x-direction,

v = Vy(x,y,z,t) = ground water velocity component in y-direction,

w = Vz(x,y,z,t) = ground water velocity component in z-direction,

α = vertical compressibility of the granular skeleton of the medium ($\alpha=1/E_S$, where E_S is Young's Modulus of elasticity),

β = compressibility of fluid (β is reciprocal of bulk modulus of elasticity),

p = pore pressure, and

n = porosity.

with the following assumptions:

- change in lateral direction is negligible as compared to vertical direction;
- volume of solid grains of aquifer is constant, because compressibility of soil grain is considerably smaller than soil skeleton;
- groundwater flow is isothermal and in an isotropic media;
- gradients of flow are small, because the water table is flat except near the discharge faces; and
- rate of movement of solid grains is very much smaller than the rate of movement of pore water.

Equation (V. 1) reduces for

Homogeneous isotropic medium as:

$$K.\left[\nabla^2 h - 2g.\beta.\rho.\frac{\partial h}{\partial z}\right] = S_s \frac{\partial h}{\partial t} \quad \text{.. (V.2)}$$

With the assumption of incompressibility the above equation for confined aquifer reduces to:

$$K\nabla^2 h = S_s \frac{\partial h}{\partial t} \quad \text{..(V.3)}$$

where:

K = coefficient of permeability (m/sec),

h = piezometric head (m), and

S_s = specific storage (m^{-1}).

For confined aquifer, the above equation reduces to:

$$\nabla^2 h = \frac{S}{T} \frac{\partial h}{\partial t} \quad \text{...(V.4)}$$

S = storage coefficient (dimensionless), and
T = transmissibility or coefficient of transmissibility (m^2/sec)

In special cases of a confined aquifer of thickness b, integration of equation (V.2) leads to a value of storage coefficient as:

$$S = \rho g(\alpha + n\beta) \quad \text{...(V.5)}$$

Transmissibility T of the aquifer is:

$$T = K.b \quad \text{..(V.6)}$$

and introducing hydraulic head h,

$$h\ (x, y, t) = \frac{1}{b}\int_0^b h\ (x, y, t)\ dz \quad \text{..(V.7)}$$

in equation (V.2) will reduce to:

$$\nabla^2 h = \left(\frac{S}{T}\right)\frac{\partial h}{\partial t} \qquad \text{(V.8)}$$

which is the same as (V.4).

For flow through fractures or joints the equation is given below[11]:

$$v = \frac{g}{12\upsilon}(2b)^2\nabla^2\phi \qquad \text{(V.9)}$$

where:

$2b$ = fracture opening (cm),

υ = viscosity of water(poise), and

ϕ = hydraulic potential

APPENDIX-VI

PARAMETERS FOR GROUNDWATER MODELLING AND THEIR INVESTIGATIVE TECHNIQUES

1. Hydraulic conductivity	Geological data, pumping tests and laboratory measurements
2. Effective porosity	Geological data, field and laboratory measurements and electrical conductivity of intergranular fluid
3. Compressibility of solid formation measurements	Geological data, laboratory
4. Soil moisture content	Geological data, field and characteristics laboratory measurements
5. Groundwater movement	Geological and lithological data, potential measurements, pumping tests, tracer techniques and water mass balance technique
6. Fluid density, viscosity and compressibility	Laboratory measurements, calculation from pressure, temperature and solute concentration measurements
7. Recharge and discharge locations and rates	Pumping tests, tracer tests, geological studies, flow measurement for man-made recharge and discharge and potential measurements
8. Time varying potential along boundaries	Potential measurements and surface water evaluations along boundaries
9. Geometric description of aquifer boundaries	Lithological and hydrogeological data and potential measurements
10. Initial potential distribution	Field measurements at wells or piezometer
11. Distribution coefficient (k_d)	Laboratory measurements

APPENDIX-VII

PARAMETERS FOR RADIONUCLIDE MIGRATION MODELLING AND THEIR INVESTIGATIVE TECHNIQUES

Data	Sources
Dispersion coefficient	Field and laboratory measurements, tracer tests and lithological data
Distribution coefficient (K_d)	Laboratory measurements, correlation with lithological field data
Radionuclide initial locations	Field samples
Radionuclide initial concentration	Field samples
Radionuclide concentrations at recharge and discharge points	Samples of waste disposal recharge streams, calculation from leaching data

APPENDIX-VIII

RADIONUCLIDE MIGRATION MODELLING

1. Generalised Hydrodynamic Model

For homogeneous and isotropic aquifer with unidimensional groundwater flux and advective transport with hydrodynamic dispersion in three dimensions, a mass balance for a saturated flow in a differential volume of the aquifer of uniform physicochemical characteristics can be represented as [12]:

$$n\left(\frac{\partial C}{\partial t}\right) + (1-n)\left(\frac{\partial q}{\partial t}\right) = nD_x\left(\frac{\partial^2 C}{\partial x^2}\right) + nD_y\left(\frac{\partial^2 C}{\partial y^2}\right) + nD_z\left(\frac{\partial^2 C}{\partial z^2}\right) - nU_x\left(\frac{\partial C}{\partial x}\right) - n\lambda C - (1-n)\lambda q \quad \text{.......(VIII.1)}$$

where C is the concentration of radionuclide in groundwater (Bq/ml); q the volumetric concentration of the radionuclide in solid phase (Bq/ml); n the porosity; D_x, D_y, D_z are hydrodynamic dispersion coefficients in x, y and z directions (cm^2/sec); U_x is the uni-dimensional (x) component of groundwater pore velocity (cm/sec); and λ the radionuclide decay constant. Assuming rapid equilibrium between solid and liquid phases, their concentrations are related by a linear formula:

$$q = K_d R_s C \quad \text{.......(VIII.2)}$$

in which K_d is the equilibrium distribution coefficient (the ratio of radioactivity per unit weight of solid phase to the radioactivity per unit volume of liquid (Bq g^{-1}/Bq ml^{-1}); and R_s the specific density of solid phase. The specific density, R_s is related to bulk density, ρ_b, (mass per unit volume of aquifer) of the medium by the relationship:

$$R_s = \frac{\rho_b}{(1-n)} \quad \text{.......(VIII.3)}$$

Substituting Eq.s VIII.2 and VIII.3 in Eq.VIII.1 gives the following conservative expression after rearrangement:

$$\left(\frac{\partial C}{\partial t}\right) = D_{x'}\left(\frac{\partial^2 C}{\partial x^2}\right) + D_{y'}\left(\frac{\partial^2 C}{\partial y^2}\right) + D_{z'}\left(\frac{\partial^2 C}{\partial z^2}\right) - U_{x'}\left(\frac{\partial C}{\partial x}\right) - \lambda C \quad \text{.............(VIII.4)}$$

where $D_{x'} = D_x/a$; $D_{y'} = D_y/a$; $D_{z'} = D_z/a$; $U_{x'} = U_x/a$ and a is the retardation factor for nuclide in the porous media obtained as:

$$a = 1 + \left(\frac{K_d \rho_b}{n}\right) \quad \text{..(VIII.5)}$$

2. Assumptions

Equation (VIII.1) which is used as the basis for all analytical models described later, has been formulated under a number of assumptions that are summarised below.

Many physicochemical and biological processes can alter the concentration of radionuclides in groundwater flow system. Among the processes are adsorption, acid-base reaction, solution/precipitation, chelation, oxidation, reduction and ionexchange. Some of these processes interact with each other, vary with time and are not necessarily reversible. Sorption of radionuclides is the only process considered here and this is assumed to be linear with medium concentration. In addition, this chemical reaction is assumed to be rapid that equilibrium exists between dissolved and sorbed radionuclides at any instant.

The orders of magnitude of molecular diffusion are assumed to be many times smaller than mechanical dispersion (convective dispersion) and hence neglected.

The aquifer has been assumed to be homogeneous and isotropic. The water flow has been considered to be uniform, steady and unidirectional.

Finally, the radionuclide effluent is assumed to have the same density as groundwater.

3. Analytical Solutions

3.1 General

Equation VIII.1 can be solved by Laplace transformation or in terms of Green functions based on mass conservation for an unit instantaneous release as:

$$C_i = \left(\frac{1}{n_e a}\right) X(x,t)Y(y,t)Z(z,t) \qquad \text{..................................(VIII.6)}$$

where C_i is the concentration of radionuclide in groundwater at any point in space for an instantaneous release; n_e is the effective porosity and X,Y,Z the Green functions in x,y,z coordinate directions respectively.

3.2 Aquifer of Infinite Dimension

The analytical solution for an instantaneous release of unit activity from a point source at (0,0,0) in an aquifer of infinite dimension is as follows:

$$C_i = \left\{\left(\frac{1}{a\, n_e}\right)\right\} X_1\, Y_1\, Z_1 \qquad \text{..(VIII.7)}$$

where:

$$X_1 = \left\{\frac{1}{(4\pi D_{x'}t)^{1/2}}\right\}\left[\exp\left\{-\left(\frac{(x-U_{x'}t)^2}{4\ D_{x'}t}\right)-\lambda t\right\}\right] \qquad \text{.................... (VIII.8)}$$

$$Y_1 = \left\{\frac{1}{(4\pi D_{y'}t)^{1/2}}\right\}\left[\exp\left\{-\left(\frac{y^2}{4D_{y'}t}\right)\right\}\right] \qquad \text{..........................(VIII.9)}$$

$$Z_1 = \left\{\frac{1}{(4\pi D_{z'}t)^{1/2}}\right\}\left[\exp\left\{-\left(\frac{z^2}{4D_{z'}t}\right)\right\}\right] \qquad \text{..........................(VIII.10)}$$

3.3 Reduction Factor for an Instantaneous Point Source

The concentration of a radionuclide at the centre-line of the plume ($x = U_x t, 0,0$) in a uniform one-dimensional flow for an instantaneous point source release of VC_o can be represented by the relation:

$$C\ (x,t) = \left(\frac{VC_o}{(4\pi t)^{3/2}\ (D_{x'} \cdot D_{y'} \cdot D_{z'})^{1/2}} \right) \qquad \text{.........................(VIII.11)}$$

where:

C_o is the initial radionuclide concentration in the effluent (Bq/ml); V the volume of the effluent released (ml); C(x,t) is the concentration of radionuclide at time t. Thus the Reduction Factor (RF) at the centre-line of plume:

$$RF = \left(\frac{C_o}{C} \right) = \left[(4\pi t)^{3/2}\ \frac{(D_{x'} \cdot D_{y'} \cdot D_{z'})^{1/2}}{2V} \right] \qquad \text{....................(VIII.12)}$$

where factor 2 has been used for reflection contribution in z plane. The minimum RF can be obtained by using D_X, D_Y and D_Z instead of $D_{x'}$, $D_{y'}$ and $D_{z'}$.

3.4 Instantaneous Release from a Line Source

The thickness (H cm) of aquifer in this case is assumed to be small and the source vertically mixed thoroughly. The solution for such a condition is given as:

$$C_i = \left(\frac{1}{n_e aH} \right) X_1\ Y_1 \qquad \text{.. (VIII.13)}$$

where H is the thickness of aquifer.

3.5 Instantaneous Release from Aerial Source

The thickness and lateral extent of aquifer are considered to be small and hence the source can be considered to be thoroughly mixed in y-z plane especially when the aquifer flow is very small. The solution for such a condition from an instantaneous unit release is as follows:

$$C_i = \left(\frac{1}{n_e aA}\right) X_1 \qquad \text{.. (VIII.14)}$$

where;

A is the cross-sectional area of the aquifer in y-z plane.

3.6 Instantaneous Release and Source Configurations

Equation VIII.6 can be developed for several boundary and source configurations. Some typical additional examples are: consideration of reflections in z direction for finite thickness; consideration of reflection in y co-ordinate for finite aquifer thickness; consideration of reflections in both finite thickness and lateral extent of the aquifer. The choice of source configuration should be based on information available for the hydrogeological unit.

4. Source Terms of Release

There exist in the literature many models, of varying complexity, for predicting spatial and temporal distribution of radionuclides in groundwater. The selection of appropriate source terms to be used as input to groundwater is very crucial in impact evaluation.

4.1 Continuous and Constant Release

Many models have considered the input to groundwater as continuous and constant. This assumption is highly conservative and unrealistic since the source in the shallow land repository decreases with time due to confinement and retention.

4.2 Leach Flux from Single Dump

One of the realistic considerations is to assume differential leaching from the waste stored in different modules such as earth trenches, RCC trenches and tile holes. This can be expressed by the relation:

$$\phi_1(t)=K_l M\cdot[\exp\{-(\lambda+K_l)t\}] \qquad \text{............................... (VIII.15)}$$

where $\phi_1(t)$ is the leach flux (Bq/s) entering groundwater; M the radionuclide inventory in the module (Bq) and K_l the leach rate coefficient for the nuclide from the module (s^{-1}). However, data on leach rate coefficients for individual radionuclides may not be available. Alternatively, the reciprocal integrity of the module can be assumed to be leach rate coefficient for all radionuclides in the absence of data. Though this concept does not distinguish variations in leaching characteristics of different radionuclides, it can be considered as a realistic conservative assumption.

4.3 Leach Flux from Multiple Dumps

Another realistic assumption is to consider a discharge rate of Q (Bq/y) for the site upto a preset period of 'T' years (about 50 years) depending on the capacity of near-surface burial facility. The build-up of radioactivity in the site is given by:

$$\frac{dM}{dt} = Q - (K_l + \lambda)M \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(VIII.16)}$$

The inventory of the waste, M (Bq), at site is represented by the relation:

$$M = \left\{\frac{Q}{(K_l + \lambda)}\right\} \cdot \left[1 - \exp\{-(K_l+\lambda)t\}\right] \text{for } 0<t<T \ \ldots\ldots\ldots\ldots\text{(VIII.17)}$$

where T is the dumping period. The corresponding leach flux ϕ_2 (Bq/s) during dumping can be obtained from the relation:

$$\phi_2 = \left\{\frac{K_l\, Q}{(K_l + \lambda)}\right\} \cdot \left[1 - \exp\{-(K_l+\lambda)T\}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(VIII. 18)}$$

The concentration of radionuclide in groundwater during post-dumping period arises out of two types of source terms namely:

- dispersional effect in post-dump period for the source that has entered the groundwater during dumping, and

- dispersional effect in post-dump period for the source that gets leached from residual amount after termination of dumping.

4.4 Accidental Release

For evaluating the effects of potential accidental releases to groundwater, it may be appropriate to perform simplified evaluations with conservative assumptions and data initially followed with refined analysis using realistic assumptions and models at second stage.

Initially it can be assumed that the entire source has been released to groundwater instantaneously and radioactive materials move with groundwater velocity (no dispersion, no sorption or no decay) to the nearest potential user situated at site boundary. Refined evaluations include use of a realistic model of the transport, hydrodynamic dispersion, decay and sorption and desorption of radionuclides for computation of concentration profile at the location of interest. The source term computation should take into account design and safety features of the facility releasing the source.

5. Concentration from Continuous Leaching

Concentration profile of radionuclide in groundwater, C(x,t) for a continuous flux arising from different modules existing at the shallow land burial site can be evaluated using the convolution integral of the form:

$$C\ (x,t)=\int_0^t \phi(t-\tau)C_i(t)d\tau \qquad \text{..(VIII.19)}$$

where τ is the time spent by radionuclide in groundwater; $(t-\tau)$ is the time, the radionuclide spent in the containment; and C_i is the concentration of radionuclide in groundwater due to an instantaneous release of unit activity. Spatial and time profile of radionuclides in groundwater can be obtained by the appropriate flux $\phi(t-\tau)$ for single or multiple inputs and the appropriate instantaneous solutions derived using line or aerial source, with or without reflections.

6. Flux Model

In many hydrogeological situations, an aquifer is connected to a body of surface water. The radioactive materials of groundwater would eventually pass onto surface water. Hence, it may be desirable to estimate the flux or discharge rate of radionuclides into surface water body. For the assumed unidirectional flow field, the flux, F (Bq/s), of a radionuclide entering surface water through an area A in y-z plane is given by:

$$F = A\ n_e \left\{ U_{x'} C - D_{x'} \frac{dC}{dx} \right\} \quad \text{..} \ (\text{VIII.20})$$

where the first term and second term in the parenthesis indicate advective and diffusional fluxes respectively.

7. Consideration of Aquifers

The pre-requisite for study of radionuclide migration in groundwater is the information on local hydrogeological systems, the existence and location of relevant aquifers, their characteristics and interrelationships among them. The geological setting of the site may indicate layers of aquifers separated by clay zones of varied thickness. A single layer model assumes the entry of leach flux directly into the aquifer. The double layer model considers migration of radionuclides in a finite layer of saturated clay medium prior to the entry into the second aquifer. The concentration of radionuclides in the clay pore water at the clay-ground water boundary is translated into flux and used as an input into the sandy aquifer. The clay layer, due to its sorptive capacity, would retard the migration of radionuclides into groundwater. The reduction in flux entering groundwater is the result of decay during transit in this zone caused by retarded velocity owing to K_d of the respective nuclides.

ANNEXURE-I

TYPICAL MONTHWISE SIX YEARLY MEAN OF TOTAL RAINFALL AND NUMBER OF RAINY DAYS AT TROMBAY (mm)

Period: 1985-90

Month	**Rainfall (mm)**	**Rainy Days (No.)**
Jan	Nil	Nil
Feb	Nil	Nil
Mar	Nil	Nil
Apr	Nil	Nil
May	66.6	2.8
Jun	670.5	18.2
Jul	734.3	28.4
Aug	725.7	28.0
Sep	271.6	20.0
Oct	122.0	4.6
Nov	1.1	0.4
Dec	4.8	0.6

ANNEXURE-II

TYPICAL MONTHLY RAINFALL AT TROMBAY (mm)

Year	Month						Annual
	May	June	July	August	September	October	
1959	-	327.5	1016	663.4	272.5	-	2279.4
1960	2.79	986.8	551.19	301.7	95.7	214.3	2152.5
1961	26.92	402.3	1324.62	473.9	289.5	139.2	2656.4
1962	13.8	192.2	1025.0	459.9	606.1	-	2297
1963	-	399.4	913.3	1025.7	358.1	30.3	2726.8
1964	-	725.7	565.9	582.1	442.5	14.6	2330.8
1965	-	603.4	1552.8	408.7	61.2	-	2626.1
1966	-	289.7	943.8	249.2	468.2	1.2	1951.1
1967	-	637.1	1212.6	376.3	234.3	20.5	2482.1
1968	-	198.5	857.1	212.3	94	47.4	1409
1969	-	712.3	614.3	164.1	352.8	-	1843.5
1970	18.0	979.6	588.1	561.2	141	21.9	2309.8
1971	98.0	742.3	398.2	645.9	357.1	45.1	2236.6
1972	-	954.1	514.4	113.1	81.8	-	1663.4
1973	-	457.8	746.8	564.2	273	243	2066.1
1974	28.4	229.9	965.9	450.5	148.1	289.8	2112.1
1975	1.0	745.2	842.0	837.8	589	64.6	3079.6
1976	-	508.1	932.5	482.2	466.8	0	2389.6
1977	-	306.0	1165.7	340.9	674.5	69.5	2556.8
1978		1003.2	628.4	231.8	149.3	32.5	2045.2
1979	-	682.9	722.0	484.1	223.3	-	2112.3
1980	-	845.5	602.6	818.3	116	14.7	2397.1
1981	-	242.7	918.9	532.7	681.6	45.9	2421.8
1982	-	285.1	846.7	574.8	126.7	87.4	1920.7
1983	-	467.3	1050.1	1229	486.2	105.4	3338
1984	-	651.9	1093.3	249.6	322.9	43.4	2361.1
1985	9.0	997.4	724.3	457.4	326.5	169.3	2683.9
1986	-	593.3	356.8	480.4	73.7	-	1504.2
1987	-	545.8	893.8	927.4	53	140.8	2560.8
1988	-	387.9	1155.4	437.4	536.2	191.1	2708
1989	-	584.0	927.0	693.8	221.9	117.4	2544.1
1990	219.2	1245.8	340.0	1092.9	499.3	186.3	3583.5
1991	-	944.4	1104.9	301.4	105.9	-	2456.6
1992	-	254.8	450.4	957	324.2	52.4	2038.8
1993	-	412.6	974.6	359.3	755.1	135.3	2636.9
1994	-	706.5	1059.7	430.3	330.8	51	2578.3
1995	-	125.2	703.6	448.8	457.6	81.5	1814.7
1996	-	192.9	1142.4	497.3	231.5	99.9	2164
1997	-	585.4	579.5	821.3	476.3	0	2462.5

ANNEXURE-IIA

TYPICAL YEARWISE MAXIMUM DAILY RAINFALL AT TROMBAY (mm)

Year	Maximum Daily Rainfall at Trombay (in mm)	Date
1959	167	June 29
1960	116	June 25
1961	163	July 25
1962	136.2	September 19
1963	194	July 6
1964	130	August11
1965	301	July20
1966	174	July19
1967	257	July 29
1968	85.6	July 30
1969	290.4	June 30
1970	197	June 17
1971	177	June 1
1972	186	June 30
1973	205	June 12
1974	292.7	July 5
1975	229.4	July 30
1976	195.2	June 5
1977	163.5	September 2
1978	164	June 15
1979	369.8	July 29
1980	191.8	August 22
1981	225.5	September 23
1982	146.2	June 19
1983	226.3	July 17
1984	205.3	July 4
1985	287.4	June 25
1986	174.2	June 22
1987	205.5	July 7
1988	145.5	July 19
1989	408.3	July 24
1990	376.6	June 16
1991	399	June 9
1992	244	August 12
1993	153.1	September 2
1994	186.4	June 28
1995	179.2	September 2
1996	203	July 22
1997	325.5	August 23

ANNEXURE-III

TYPICAL MONTHLY RAINFALL FOR THE YEARS 1961 TO 1995 AT TARAPUR (mm)

	Month												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
1961	-	-	-	-	-	222.2	1028.5	339.8	176.5	-	-	-	1767
1962	-	-	-	-	-	193.2	860.3	290.1	263.6	22.3	-	-	1629.5
1963	-	-	-	-	-	251.1	1088.2	675.3	103.3	65.4	-	-	2183.3
1964	-	-	-	-	-	711.6	518.7	425.1	185.2	-	-	-	1840.6
1965	-	-	-	-	-	456.3	874.3	231.7	119.1	-	-	-	1681.4
1966	-	-	-	-	-	342.4	776.2	65	242.3	-	-	-	1425.9
1967	-	-	-	-	-	794	973.7	187.3	168.2	38.2	-	-	2161.4
1968	-	-	-	-	-	77.3	457.9	328.9	151.3	10.3	-	-	1025.7
1969	-	-	-	-	-	371.1	740.5	278.5	382.6	3.3	3	-	1779
1970	-	-	-	-	15.4	989.6	585.3	916.2	294.2	49.7	-	-	2850.4
1971	-	-	-	-	66.2	641.6	351.9	695.9	467	4.8	-	-	2227.4
1972	-	-	-	-	-	325	336.2	275.6	45.6	0.3	-	-	982.7
1973	-	-	-	-	-	436.6	600.8	290.1	294.9	-	-	-	1622.4
1974	-	-	-	-	45.0	45.7	1126	270.8	163.6	101.5	-	-	1752.6
1975	-	-	-	-	6.6	520.9	611.1	484.5	318.4	42.1	-	-	1983.6
1976	-	-	-	-	-	380.1	880.1	515	212.3	43.3	37.2	-	2068
1977	-	-	-	-	-	470.2	590.6	109.9	377.2	4.6	52.5	-	1605
1978	-	-	-	-	6.8	471.1	309.4	92	44.9	70	33	-	1027.2
1979	-	31.5	-	-	-	462.3	363.7	648.1	102	0.4	100.2	-	1708.2
1980	-	-	-	-	-	498	465.6	478.1	80.7	-	2.2	9	1533.6
1981	-	-	-	-	-	222	603	658	643.8	29	11.9	-	2167.7
1982	-	-	-	-	-	214.9	735.4	388.4	238.7	-	63.3	-	1640.7
1983	-	-	-	-	-	299.6	972.4	1106.6	445.2	269.9	-	-	3093.7
1984	-	-	-	-	-	434	543.4	212.4	56.6	41.3	-	-	1287.7
1985	-	-	-	-	6.5	245.6	506	322.7	42.9	133.3	-	-	1257
1986	-	-	-	-	-	390.7	181.4	266.5	21.2	-	0.7	13.6	874.1
1987	-	-	-	-	-	288.9	376	559.1	48.3	9.7	1.4	12.4	1295.8
1988	-	-	-	-	-	244.1	1054.9	369	425	11.9	-	-	2104.9
1989	-	-	-	-	1.3	419.7	599.3	206.7	109.9	16.3	-	-	1353.2
1990	-	-	-	-	370-5	321.2	252.8	313.9	497	124.1	9-1	-	1888.6
1991	-	-	-	-	-	306.1	1091.9	183.4	60.7	-	-	-	1642.1
1992	-	-	-	-	-	132.8	332.8	545.4	549.3	0.5	-	-	1560.8
1993	-	-	-	-	-	718.3	680.9	260.7	543.1	161.9	-	-	2364.9
1994	29.8	-	-	-	-	797.6	875.5	603.7	192.3	57.3	-	-	2556.2
1995	-	-	-	-	6.3	42.7	754.3	154.2	220.2	1.2	-	-	1178.9
Ave.	0.9	0.9	-	-	15.0	392.5	660	392.88	236.8	37.5	9	1	1746.3

ANNEXURE-IIIA

TYPICAL DAILY AVERAGE RAINFALL FOR THE YEARS 1961-94 AT TARAPUR (mm)

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	0	0	0	0	4.7	29.8	25.3	13.4	3.9	0	0
2	0	0	0	0	0	3.7	24.4	23.4	19.6	5.8	0.3	0
3	0	0	0	0	0	4.7	38.2	10.1	11.7	1.1	0.1	0
4	0	0	0	0	0	6.7	23.8	24	7.8	2.6	0	0
5	0	0	0	0	0	4	39.1	14.4	10.8	0.9	0.3	0
6	0	0	0	0	0	3.4	14.6	24.8	9	1.7	0	0
7	0	0	0	0	0	10.8	16	10.6	7	1.9	0	0
8	0	0	0	0	0	5.8	13.5	12.9	6.8	4.1	1.3	0
9	0	0	0	0	0	6.5	24.8	7.9	8.1	1.9	1.3	0
10	0	0	0	0	0	8.4	15.1	14	5.7	1.1	0.1	0
11	0.9	0	0	0	0	10.2	17.4	17.7	2.9	1.6	0.1	0
12	0	0	0	0	0	14.2	13	16.3	2.7	0.8	0	0.4
13	0	0	0	0	0	20	19.1	19.4	4	0.9	0	0
14	0	0	0	0	0	13.4	20.8	16.2	2.5	1.9	0.2	0
15	0	0.9	0	0	0	20.3	28.9	9	3.6	0.1	0.8	0
16	0	0	0	0	0.2	24.5	44.6	8.1	5.9	2	1.1	0
17	0	0	0	0	0	17.2	25.3	7.7	5.6	1	0.2	0
18	0	0	0	0	0	16.9	25.3	13.6	6.2	0.2	0.1	0
19	0	0	0	0	0	19.2	22.8	16.5	6.5	0.3	0.5	0
20	0	0	0	0	0	13.9	9.9	11.9	3.9	2.1	0	0
21	0	0	0	0	0	15.7	14.1	7.3	4.2	0.3	0.4	0
22	0	0	0	0	0	13.9	22.8	6.3	9.7	0.2	0.4	0.2
23	0	0	0	0	0	15.3	16.6	7.3	17	0.3	0.3	0
24	0	0	0	0	0	18.3	20	9.3	16.8	0.3	0	0
25	0	0	0	0	0	14.3	17.5	9.8	8.4	1	0	0
26	0	0	0	0	0.5	15.2	11.5	6.1	8.8	0.2	0	0
27	0	0	0	0	0.6	20.2	19.3	6.6	6.9	0	0.9	0.4
28	0	0	0	0	4	16.9	19.6	8.3	10.4	0.1	0.8	0
29	0	0	0	0	1.6	21.7	15.4	9.6	7.3	0.1	0.2	0
30	0	0	0	0	4	23.1	11.5	17.4	4.2	0.3	0	0
31	0	0	0	0	4.3	0	22.3	8.2	0	0	0	0
Total	0.9	0.9	0	0	15.2	402.8	657.2	399.8	237.3	38.6	9.3	1

Yearly average total: 1763.0

ANNEXURE-IV

METHODS AND FREQUENCIES OF MEASUREMENTS WITHIN THE MONITORING PROGRAMME

Groundwater	Methods	Frequency
Water table	Piezometric analysis	Twice a year (pre- and post-monsoon)
Chemistry	Chemical analysis	Twice a year (pre- and post-monsoon)
Radiochemistry	Radiometric analysis	Twice a year (pre- and post-monsoon)
Velocity and direction of flow	Tracer tests/calculations from hydraulic gradient	Pre-, during and post-monsoon

ANNEXURE-V [12,13,14]

SENSITIVITY ANALYSIS AND UNCERTAINTY OF ANALYSIS FOR MIGRATION OF RADIONUCLIDES FROM SHALLOW LAND BURIAL FACILITIES

Introduction

Mathematical models have been developed to predict the spatial and temporal profiles of radionuclide concentration in the near-field and far-field of a shallow land burial facility[12]. This disposal facility considered is a reinforced concrete vault located 2.9 m above the highest water table. The source term is derived from leaching considerations based on diffusion-controlled kinetics for the transfer of radionuclides from the cylindrical waste form into the surrounding pore water of the backfill material. The concentration of radionuclides in the backfill at the bottom boundary of the vault is converted to a release rate into the near-field using the outgoing water flux. The delay and decay during transit in sand and soil layers are taken into account while evaluating concentration and release at the near-field water table boundary. Taking this release rate as the inlet flux, the concentration of radionuclides in groundwater has been computed using a two-dimensional model. Results indicate that vault facility with cement as backfill material could contain almost all radionuclides commonly encountered in waste stream generated during operation of nuclear power plants. However, the storage of some of the long-lived radionuclides produced in fuel reprocessing plants such as ^{79}Se, ^{99}Tc, and ^{129}I in the vault facility need to be regulated for restricting the resultant dose within the apportioned dose limit prescribed for the facility.

The nuclide dependent parameters and nuclide-independent parameters used for computations are given in Table-1 and Table-2 respectively. The maximum concentrations and release rates of radionuclides at the bottom boundary of disposal facility and in the nearfield are shown in Table-3.

Sensitivity Analysis

A comparison of ^{14}C concentrations in groundwater derived using three different methods such as Codell's program, Simpson's rule, and Gauss quadrature is given in Table-4. Codell et al [13] employed digitized input of radioactivity flux into the groundwater. The release rate of ^{14}C calculated using this program is also digitized and introduced into Codell's program to evaluate its concentration profile in the groundwater. As can be seen from Table-4, this exercise shows good agreement between different methods indicating computational efficacy of this model.

The sensitivity of intrinsic diffusivity D_c in waste form, on the peak concentrations of three typical radionuclides, i.e. ^{99}Tc, ^{226}Ra, and ^{90}Sr at the bottom boundary of the facility, has been studied keeping all other parameters the same as in Table-1 and Table-2. The concentration profiles of these radionuclides (Fig-V.1) follow a power law relation with D_c such as peak concentration, C_b of ^{99}Tc = $2.45x10^1D_c^{0.65}$; C_b of ^{226}Ra = $3.64x10^2D_c^{0.67}$; and C_b of ^{90}Sr = $2.28x10^5D_c^{0.69}$. The slope and correlation coefficient for this power relation are 0.7 and 0.98, respectively. The peak concentrations of all three radionuclides increased by about four orders magnitude for a variation of D_c from 2×10^{-10} to 2×10^{-5} cm^2/s. The value of D_c used in this study is experimentally determined ($1.8x10^{-6}$cm^2/s) and lies in the upper range of this variation.

The sensitivities of certain parameters in the backfill such as pore water velocity U_b, dispersion coefficient D_b, and concentration factor K_d on the near-field and far-field concentrations of two typical long-lived radionuclides, such as ^{129}I and ^{230}Th, are shown in Table-5. It is evident that ^{129}I is almost insensitive to the parameters like U_b, D_b and K_d since enhanced retardation, resulting from changes in parameters, is still inadequate to cause substantial increase in transit time compared with the half-life of this radionuclide. However, significant changes in near-field and far-field concentrations of ^{230}Th are observed due to variations in these parameters. The K_d value of ^{230}Th is high, and any further increase in retardation would result in a long transit time to allow sufficient decay, thereby, lowering its concentration. Thus, this sensitivity analysis reveals that long-lived radionuclides having low and medium K_d values will eventually find their way to far-field environment.

The sensitivity analysis has also been carried out to identify critical parameters, which have maximum effect on the concentration of ^{129}I in groundwater at 1.5 km from the facility. The sensitivity index for change of a candidate parameter can be defined as [14]:

$$S_1 = \frac{1 - \frac{C_R}{C}}{P_1}$$

where C_R is the maximum concentration for reference level and C the maximum concentration computed using candidate parameter P whose impact is to be evaluated. The index P_1 is defined as $[1-\{P/P_R\}]$ for a decrease of candidate parameter in relation to reference parameter P_R and as $[1-\{P_R/P\}]$ for an increase of candidate parameter. The sensitivity indices of different parameters are given in Table-6.

The negative sign of sensitivity index indicates that concentration decreases with respect to reference level whereas the positive sign indicates the reverse process. The relative magnitude of change in concentration is not constant for decrease and increase processes indicating nonlinearity in many cases. The most sensitive parameter is found to be as distribution coefficient followed by seepage velocity, dispersivity and thickness of unsaturated zone. The sensitivity indices shown above are more applicable for long-lived and less sorbing radionuclides. For short-lived and high sorbing radionuclides, the magnitude of these indices may vary considerably.

Uncertainty Analysis

The uncertainty analysis provides a quantitative estimate of range of model outputs that results from uncertainties in the inputs to the model. If the analysis is carried out appropriately, the output range will contain the true value that the model seeks to predict.

Probability density functions are constructed for parameters such as barrier integrity, distribution coefficient, thickness of unsaturated zone, groundwater velocity and dispersivity [14]. The uncertainties in these parameters are propagated through the model using random selection of parameters (100 sets) to generate the cumulative probability distribution of predicted radiation dose to a member of the critical group due to near-surface radioactive waste disposal practice. The peak annual effective doses (Table-7) obtained through uncertainty analysis fall in a log normal distribution. Statistical analysis indicates that the range of annual effective doses lies between $1.7\text{x}10^{-4}$ and 4.1 mSv. The geometric mean of distribution is estimated as $3.6\text{x}10^{-2} \pm 3.9$ mSv. The most probable annual effective dose is obtained as $2.8\text{x}10^{-4}$ mSv. The effective dose computed is total due to 17 radionuclides commonly encountered in near-surface disposal facilities. Their inventories correspond to radioactive waste generated per GWY energy production.

TABLE-1

NUCLIDE-DEPENDENT PARAMETERS

Nuclide	**Half-life (y)**	**Inventory (Bq)**	**Concentration Factor K_d (ml/g)**		
			Waste Form[a]	**Sand**	**Soil**[b]
^{14}C	5.73 E+3	1.0 E+10	5.0 E+3	5.0	2.0
^{60}Co	5.30	1.0 E+11	2.0 E+4	1.5 E+1	9.0 E+1
^{63}Ni	1.00 E+2	1.0 E+12	5.0 E+3	4.0 E+2	9.0
^{79}Se	6.50 E+4	1.0 E+7	2.0	1.5 E+2	5.0
^{90}Sr	2.88 E+1	1.0 E+12	2.0	1.5 E+1	8.0
^{99}Tc	2.13 E+5	1.0 E+7	1.0	0.1	0.5
^{129}I	1.70 E+7	1.0 E+7	3.0 E+1	1.0	5.0
^{137}Cs	3.02 E+1	1.0 E+12	2.0	2.8 E+2	1.0 E+2
^{226}Ra	1.60 E+3	1.0 E+9	8.0	5.0 E+2	1.1 E+2
^{230}Th	7.70 E+4	1.0 E+9	5.0 E+3	3.0 E+3	1.5 E+3

a: same K_d values are used for backfill
b: same K_d values are used for groundwater

TABLE-2

NUCLIDE-INDEPENDENT PARAMETERS

Waste Form	**Backfill**	**Sand**	**Soil**	**Groundwater**
Pore water velocity (cm/s)				
	1.9 E–6	5.0 E–3	1.0 E–5	1.2 E-5
Diffusivity (cm^2/s)				
1.8 E–6	4.3 E–6	-	-	1.2 E-3
Total Porosity				
1.5 E–1	1.5 E–1	3.8 E–1	3.1 E–1	3.0 E–1
Bulk Density (g/ml)				
1.3	1.3	1.9	1.6	1.6
Thickness (cm)				
	3.1 E+2	9.0 E+1	2.0 E+2	5.0 E+2

TABLE-3

MAXIMUM CONCENTRATIONS AND RELEASE RATES OF RADIONUCLIDES

Nuclide	Bottom Boundary of the Facility		Near-field: 2.9 m below the Facility	
	Maximum concentration (Bq/ml)	Maximum release rate (Bq/y)	Maximum concentration (Bq/ml)	Maximum release rate (Bq/y)
^{14}C	4.60 E–14	2.32 E–6	4.60 E–14	2.32 E–6
^{60}Co	0	0	0	0
^{63}Ni	0	0	0	0
^{79}Se	2.66 E–3	1.34 E+5	2.66 E–3	1.34 E+5
^{90}Sr	2.40 E+1	1.21 E+9	1.23 E+1	6.21 E+8
^{99}Tc	4.51 E–3	2.27 E+5	4.51 E–3	2.27 E+5
^{129}I	1.85 E–4	9.34 E+3	1.85 E–4	9.34 E+3
^{137}Cs	2.69 E+1	1.35 E+9	1.11 E–2	5.57 E+5
^{226}Ra	5.84 E–2	2.95 E+6	4.97 E–2	2.50 E+6
^{230}Th	1.37 E–5	6.88 E+2	1.30 E–5	6.57 E+2

TABLE-4

CONCENTRATION OF ^{14}C IN GROUNDWATER AT 500m, COMPARISON BETWEEN DIFFERENT METHODS

Time (y)	Codell's program	Simpson's Rule	Gauss Quadrature
1.0 E+5	5.49 E–21	3.25 E–21	3.25 E–21
1.5 E+5	1.93 E–15	1.87 E–15	1.87 E–15
2.0 E+5	1.58 E–15	1.54 E–15	1.54 E–15
2.5 E+5	1.09 E–17	9.44 E–18	9.44 E–18
3.0 E+5	1.51 E–20	1.29 E–20	1.29 E–20
3.5 E+5	3.24 E–23	1.94 E–23	1.94 E–23
4.0 E+5	3.87 E–26	3.37 E–26	3.37 E–26
4.5 E+5	0	6.12 E–29	6.12 E–29

TABLE-5

SENSITIVITY OF CERTAIN PARAMETERS ON THE PEAK CONCENTRATION OF RADIONUCLIDES IN THE NEAR FIELD AND FAR-FIELD

U_b (cm/s)	D_b (cm^2/s)	K_d (ml/g)	Peak Concentrations (Bq/ml)		
			Near Field	Far Field Groundwater	
			2.9m below the facility	500m	1600m
^{129}I					
3.2 E–6	4.28 E–6	3.0 E+1	1.69 E–4	1.66 E–5	6.47 E–6
1.9 E–6	4.28 E–6	3.0 E+1	1.89 E–4	1.49 E–5	6.08 E–6
6.34 E–7	4.28 E–6	3.0 E+1	2.11 E–4	7.86 E–6	4.19 E–6
1.9 E–6	1.9 E–6	3.0 E+1	2.29 E–4	1.57 E–5	6.23 E–6
1.9 E–6	4.28 E–6	3.0 E+1	1.89 E–4	1.49 E–5	6.08 E–6
1.9 E–6	9.51 E–6	3.0 E+1	1.42 E–4	1.31 E–5	2.04 E–6
1.9 E–6	4.28 E–6	3.0 E+1	5.69 E–4	1.68 E–5	6.77 E–6
1.9 E–6	4.28 E–6	3.0 E+1	1.89 E–4	1.49 E–5	6.08 E–6
1.9 E–6	4.28 E–6	3.0 E+2	4.40 E–5	4.98 E–6	2.76 E–6
^{230}Th					
3.20 E–6	4.28 E–6	5.0 E+3	2.72 E–5	1.02 E–10	2.06 E–20
1.90 E–6	4.28 E–6	5.0 E+3	1.30 E–5	4.49 E–11	9.47 E–21
6.34 E–7	4.28 E–6	5.0 E+3	3.88 E–7	8.01 E–13	2.05 E–22
1.90 E–6	1.90 E–6	5.0 E+3	1.63 E–5	4.53 E–11	9.33 E–21
1.90 E–6	4.28 E–6	5.0 E+3	1.30 E–5	4.49 E–11	9.47 E–21
1.90 E–6	9.51 E–6	5.0 E+3	8.92 E–6	5.28 E–12	6.18 E–21
1.90 E–6	4.28 E–6	5.0 E+2	2.89 E–4	2.84 E–10	5.77 E–20
1.90 E–6	4.28 E–6	5.0 E+3	1.30 E–5	4.49 E–11	9.47 E–21
1.90 E–6	4.28 E–6	5.0 E+4	2.92 E–13	1.97 E–18	5.63 E–28

TABLE-6

SENSITIVITY INDICES WITH RESPECT TO THE REFERENCE LEVEL WASTE DISPOSAL FACILITY

Parameter	Sensitivity Index	Change of Parameter
Groundwater velocity	+0.67	Decrease
	–0.66	Increase
Seepage velocity	–6.20	Decrease
	+0.88	Increase
Thickness of unsaturated zone	+0.85	Decrease
	–1.30	Increase
Dispersivity	+0.76	Decrease
	–2.40	Increase
Porosity	+0.28	Decrease
	–0.38	Increase
Distribution coefficient	+0.80	Decrease
	–6.90	Increase
Barrier integrity	+0.18	Decrease
	–1.10	Increase

TABLE-7

FEW RESULTS OF UNCERTAINTY ANALYSIS

Parameter Set No.	Peak Annual Dose (mSv)	Peak Arrival Time (y)	Critical Nuclide
1	1.73(−2)	2.35(3)	^{129}I
2	7.09(−1)	9.21(4)	^{129}I
3	2.82(−1)	4.85(3)	^{129}I
4	8.42(−3)	7.55(3)	^{129}I, ^{14}C
5	1.46	1.81(4)	^{129}I
6	5.28(−3)	1.75(3)	^{129}I, ^{14}C
7	1.84	1.20(5)	^{129}I
8	6.77(−3)	6.05(3)	^{129}I, ^{14}C
9	2.43	3.61(4)	^{129}I
10	4.12	3.61(4)	^{129}I
11	4.28(−4)	4.65(3)	^{129}I, ^{14}C
12	1.99(−3)	2.41(4)	^{129}I, ^{14}C

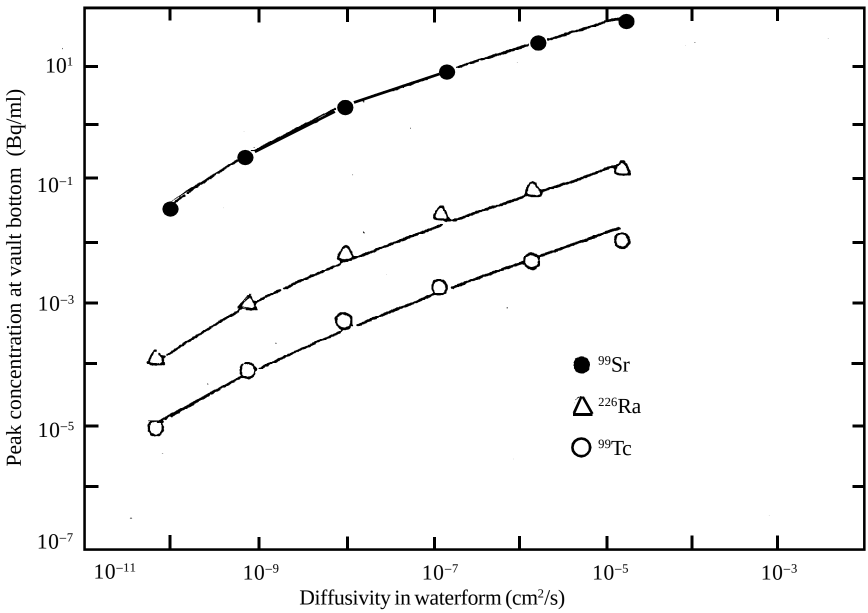

Fig. V.1. SENSITIVITY OF INTRINSIC DIFFUSIVITY IN THE WASTE FORM ON THE PEAK CONCENTRATIONS OF THREE TYPICAL RADIONUCLIDES AT THE VAULT BOTTOM

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May 15, 1992
June 11 & 17, 1992
July 7 & 20, 1992
September 15, 1992
October 1 & 15, 1992
November 18 & 24, 1992
January 5 & 20, 1993
February 2, 1993
September 2 & 30, 1993
February 24, 1994
January 13, 1995
March 1, 1995
July 8 & 24, 1997
August 13, 1997
September 8, 1997

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PROVISIONAL LIST OF SAFETY GUIDES UNDER SITING CODE

Safety Series No.	Provisional Title
AERB/SC/S	Code of Practice on Safety in Nuclear Power Plant Siting
AERB/SG/S-1	Meteorological Dispersion Modelling
AERB/SG/S-2	Hydrological Dispersion of Radioactive Materials in Relation to NPP Siting
AERB/SG/S-3	Extreme Values of Meteorological Parameters
AERB/SG/S-4	Hydrogeological Aspects of Siting of NPPs
AERB/SG/S-5	Models for Radioactive Dose Computation Methodologies from Radioactivity Concentrations in Environment.
AERB/SG/S-6A	Design Basis Flood for NPPs at Inland Sites
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AERB/SG/S-8	Influence of Site Parameters on Emergency Preparedness
AERB/SG/S-9	Population Distribution and analysis in relation to siting of NPPs
AERB/SG/S-10	Quality Assurance in Siting
AERB/SG/S-11	Seismic Studies and Design Basis Ground Motion for NPP Sites.

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