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HYDROGEOLOGICAL ANALYSIS OF SAFE RADIOACTIVE WASTE DISPOSAL

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Abstract: The construction of radioactive waste repositories represents a specific problem connected with eliminating its negative impact on the landscape ecosystem. An analysis of the factors decisive for the hydrogeological evaluation of the rock mass as related to safe radioactive waste disposal is presented. The specificity of the solution stems from the long-term toxicity of the waste. Selection of the repository site requires a comprehensive systemic approach. One of the decisive and limiting criteria is the analysis of hydrogeological factors.

A depth zone of the hydrogeological massif with permeability of the order of 10^{-9} m.s^{-1} and less represents the most suitable medium for safe disposal of radioactive waste of all types. The analysis of hydrogeological conditions indicates that disposal of radioactive waste in surface repositories is not suitable.

Key words: radioactive waste; hydrogeological factors; evaluation; safety repository; massifs; low hydraulic conductivity; geomechanical stability

1. DISPOSAL OF RADIOACTIVE WASTE

The disposal of radioactive waste represents an anthropogenic process which disrupts the homeostasis of the ecological system in the biosphere, i.e. in part of the lithosphere, the atmosphere and in the hydrosphere as a whole. Radioactive waste is characterized by long-term toxic effects on the environment. Time has to be considered in geological terms, especially if highly active waste is being deposited. The long-term existence of the waste in the rock medium thus requires a specific approach to selecting and evaluating the site of a future repository. In principle, the site of the repository should be chosen so that geological processes, generated in the course of tectonic, erosion, seismic and other cycles, would in future affect it least. In view of the changes caused by the geological evolution of a particular structure, no natural material can be considered completely impermeable. The increased generation of heat due to the decay of radioactive elements creates conditions for long-lasting interaction between water and rock.

Water is one of the fundamental elements responsible for the interaction between the separate components of the ecosystem, because it mediates the exchange and propagation of substances not only within the system, but also between the separate ecological systems. The part played by water in natural metabolism in the biosphere

Table I. Relationship of radiactive waste disposal options (adapted in accordance with IAEA, Safety Series 54, 1981)

		Long-term waste disposal		Short-term waste disposal	
		Category of radioactivity			
		High level	Intermediate level Low level	Intermediate level	Low level
Deposition storage in deep structures (c)	(a)	Solid, immobilized, packaged, spaced for heat dissipation	Solid, immobilized, packaged	Applicable (e)	
	(b)	As above; additional engineered barriers necessary	As above; possible engineered barriers necessary		
Deposition storage in mines of cavities (d)	(a)	Not recommended	Possible, depending on conditions	Solid, may be packaged (e)	
	(b)	Not recommended		Solid, immobilized, packaged (e)	
Deposition at shallow depths	(a)	Not recommended		Solid, immobilized, packaged	Solid, packaged
	(b)	Not recommended		As above; additional protective measures necessary	
Injection of self-solidifying fluids into induced cracks in isolators (low-permeability strata)		Not recommended	May be possible with adequate proved technology and suitable radionuclides	Applicable with appropriate technology of construction and waste disposal	
Injection of liquid active waste into deep aquifers		Not recommended	As above	As above	

Notes to Table I: (a) Geological environment naturally isolated from groundwater flowpaths (dry). (b) Geological environment with limited flow of groundwater (wet). (c) Repository excavated especially for radioactive waste disposal. (d) Workings created by extraction of mineral raw materials, cavities created by natural processes, or excavated especially for radioactive waste disposal. (e) May be preferred in areas with unfavourable geological conditions at shallow depths.

is the primary factor to be considered in selecting radioactive waste repositories. The second most important factor is time as related to the decay of radioactive substances. The original tectonic, hydrogeological and geotechnical conditions of the waste repository should not change in this time interval. As the basic interval with regard to the invariability of repository's environment one should consider intervals of 10^3 to 5×10^5 years (Farvolden *et al.*, 1985). The past evolution and state of safe radioactive waste disposal indicates that this problem has not been solved satisfactorily on a worldwide scale (Pačes, 1987).

The characteristic feature of radioactive waste from nuclear power plants is its long-term toxicity. Due to radioactive decay this waste has to be considered an active substance being deposited in the natural environment. The repository site has to be stable and resistant to anthropogenic and natural effects in view of possible repository accidents and the subsequent difficult liquidation of the contaminated part of the lithosphere and hydrosphere.

In terms of radioactive emission, radioactive waste can be divided into waste with low, intermediate and high level of activity, in terms of decay into long-term and short-term. These are factors to be considered in selecting the repository site. Table I shows the basic criteria for and methods of radioactive waste disposal. Table II gives the advantages and disadvantages of the basic rock types suitable for radioactive waste disposal. Tables I and II indicate that the most suitable medium for safe radioactive waste disposal are deep zones of the hydrogeological massif, i.e. a massif formed by structural units of the basement.

2. HYDROGEOLOGICAL ANALYSIS OF THE REPOSITORY SITE

In selecting the site for constructing a radioactive waste repository it is necessary to consider a set of factors which can be divided into geological and geophysical, hydrogeological and geotechnical. The analysis of the factors is based on the following criteria:

- construct repositories in geological formations with low hydraulic conductivity;
- locate repositories in areas with low probability of changes of the tectonics and erosion cycles, and with very limited anthropogenic activity.

(a) Geological and geophysical factors

The analysis of the rock mass is based on a systemic approach of utilizing all available sources of information in an effort to obtain a comprehensive targeted view of the construction and the disturbance of the area in question. As regards geology, data on tectonic elements and features from topograhic maps and maps of geological structures are processed, together with data from satellite and aerial surveys of the Earth, from maps of surface geophysical measurements (aeromagnetic maps, maps of conductive zones and block boundaries, delimitation of the near-surface zone), morphological maps of structure of the Quaternary cover, etc. An integral part of this procedure is the tectonic evaluation of the evolution of the area of interest,

Table II. Rock characteristics for selecting radioactive waste repositories (after R.N. Farvolden *et al.*, 1985)

Rock (host media)	Advantages	Disadvantages
Salt deposits (anhydrite)	Low permeability; high heat conductivity; high mechanical strength; self-heating (halite); joint occurrence.	Potential long-term stability; dissolution problem; occurrence near oil deposits; salt domes often small; bedrocks can be aquifers; brine migration to heat source; economic mineral. Brittle anhydrite could start fracturing at repository temperatures; anhydrite is water soluble (hydrates) and does not self-heal.
Shales, clays	Low permeability and solubility; high sorptive capacity; possible plastic flow; joint occurrence.	Physical parameters easily changed by heat (sorptive capacity reduced); often fractured and faulted; inhomogeneities affect stability; difficult to mine and keep open; rock often associated with mineral and oil deposits.
Tuffs, neovolcanic rocks	High sorptive capacity, especially tuffs in association with zeolites. Welded tuffs have high density; low water content; unfractured high temperature resistance, widely spread in places without occurrence of mineral deposits; easy to mine.	Tuffs may locally display significant fracture permeability. Neovolcanics have often been distinguished for significant flow paths. Vertical cooling joints may occur; frequent occurrence of fissures.
Plutonic and metamorphic crystalline rocks	High mechanical strength; low porosity and permeability (unfractured rocks); reduced permeability of fractures with depth; good heat properties; potential for high sorptive capacity in fracture fills; possibility of self-heal by mineral deposition in fractures; abundant occurrences.	Potential for occurrence of highly saline waters at depth (preferred flow paths); often abundant discontinuities (shear zones); dykes.

including the determination of the hierarchy of fault and fissure structures the run of the near-surface acquifer, which is usually of regional extent.

The objective of the analysis is to obtain a comprehensive regional view of the area, which is then used to determine the most suitable locality for a detailed survey. The surface methods are then supplemented by measuring the parameters and characteristics of the rock mass at depth (Socha, 1983).

Detailed mapping of bore cores, rock composition and especially of the filling of rupture-prone elements is carried out in connection with drilling. Boreholes are situated in fissure and fault structures, identified from surface measurements, their purpose being to verify the assumed properties and characteristics in the depth of the massif. A part of the survey is logging in all boreholes to delimit the tight and conductive sections in the depth interval, determine the orientation, frequency and width of fissures and faults, their mutual positions, nature of their filling and porosity.

The results of analyzing the geological data is the delimitation of conducting fissure zones for water flow in the hydrogeological massif, or hydrogeological basin. By fissure one understands free space between surfaces of discontinuity in the rock medium, irrespective of their origin, orientation or place of occurrence (Hanzlík, 1985). The complexity of analyzing these factors is caused by the anisotropy and heterogeneity of the fissure medium in the hydrogeological massif.

A necessary part of the analysis is the evaluation of the seismic hazard of the locality. Seismic effects also have their hydrogeological impacts, namely in sudden changes of the piezometric groundwater level and in its chemical composition (Hanzlík, 1990).

(b) Hydrogeological factors

The hydrogeological aspect of evaluating a radioactive waste repository takes into account

(1) the tightness of the massif as a structural block as compared with the surrounding blocks,

(2) the permeability of the rock medium,

(3) the migration of elements from the repository with regard to the long-term waste-rock-water interaction.

(1) The structural geology of the hydrogeological massif is the most important factor for the creation and circulation of fissure groundwater. As regards the aquifer system as a whole, it is not important whether it involves magmatites or crystalline rocks. Groundwater discharges from hydrogeological massifs, especially crystalline, are differentiated by their tectonic structure, by their morphological and structural development, precipitation record, and the extent of the near-surface zone. With regard to the tightness of the rock mass, disjunctive surfaces may have positive and negative impact (Hanzlík, 1985). The details display considerable variability, however, on a wider national scale it is possible to derive the dependence of permeability on the tectonic pattern. It should be realized that, besides distinctive conducting fault structures, there are also numerous fissure systems and belts with hydrogeological bearing. Consequently, it is important to establish the hierarchy of the fissure and fault structures to define the hydrological model of groundwater flow in the fissure groundwater body.

(2) The result of analyzing the set of hydraulic parameters, hydrological observations and logging measurements is the determination of the massif's permeability.

Hydrogeological survey of surface phenomena and objects

This is based on hydrogeological mapping in which spring outflows, shallow and deep wells, water courses and their watersheds, water surfaces, marshes, and drainages in the area are monitored and evaluated. This evaluation is the basis for selecting objects suitable for monitoring the changes in regime already prior to the construction of the repository. This net of observation points is included in the future stages in the system of monitoring the hydrological changes in the selected area. A part of this are the measurements of the water discharge in the end sections of water courses. The time-space analysis of hydrograms serves to establish the effects of permeable fault and fissure structures on the hydrological conditions as compared with the results of the geological and geophysical survey of the surface.

Hydrogeological survey of the rock mass at depth

The purpose of this survey is to delimit the permeable zones of the future repository at depth. Experience indicates that one cannot rely just on general facts concerning the connection of fissures at depth. Based on structural and tectonic predisposition, it is frequently possible to identify zones with different conductivities which have a hydrogeological bearing, e.g., different fissure groundwater levels in the separate zones. Monitoring the fissure groundwater level in the massif and its fluctuations provides important information also about the seismic events in the surveyed area.

Detailed logging measurements are made in trial holes using a set of methods which determine the points of inflow, losses or overflows of groundwater, the rate of flow inside the hole, the water level in the hole, the discharge level of the groundwater body, and the direction in which the water moves in the aquifer. This work is followed by hydrodynamic tests designed to determine the hydraulic parameters of the rock mass. i.e. hydraulic conductivity, transmissivity, accumulation and others. Water-pressure tests of zone tightness are also conducted in the holes. The heterogeneity and anisotropy of the hydrogeological massif require both types of tests to be made using the packer method.

Attention should be drawn to the necessity of a careful selection of methods used to analyze hydrodynamic tests. The unilateral application of non-stationary flow methods need not always be successful if the basic technical conditions for measuring the initial data for calculations have not been created, e.g., non-uniform pumping of water, fluctuations of the groundwater level in the course of pumping the water from the hole, etc. The stationary flow method can be used to an advantage for calculating the parameters in a number of cases.

Important information is provided by isotopic analyses of fissure groundwater, in particular by determining the specific activities of natural tritium nuclides, radiocarbon 14, and determining the contents of stable isotopes of deuterium, oxygen 18, carbon 13, etc. The results enable one to determine the time for which the recharged water is retained in the rock mass, as well as its origin.

The groundwaters of a hydrogeological massif are usually of the nature of extraction waters of the petrogenic type, whose mineralization increases with depth. Highly mineralized salt waters, whose inflows are not negligible, occur in deeper magmatite zones. These waters are mostly highly aggressive. The chemical composition of groundwater represents another important factor in the overall analysis, with a view to designing the construction technology, as well as to the hydrochemical research into water genesis. Particular emphasis should be put on the cleaning of holes of drilling fluids to ensure that the water sampling is representative.

Table III gives an overview of the characteristics of the rock mass and of the methods of determining them for the hydrogeological analysis.

The accuracy and reliability of evaluating a hydrogeological massif with respect to the selection of a radioactive waste repository site primarily depends on the standard of the methods of determining the necessary parameters and adherence thereto in applications. The specificity of the problems thus requires the field measurements and observations to be made in stages while preserving the necessary degree of comprehensiveness. Consequently, a combination of special boreholes (e.g., narrow holes) is covenient in order to obtain a larger number of point data within an area due to the high heterogeneity of the hydrogeological massif. It is also necessary to modify existing laboratory methods of processing rock samples of large volumes (bore cores 2.2 m long and 1 m in diamater; Witherspoon, 1979).

(3) The migration of elements from the radioactive waste repository into the neighbourhood is related to, *inter alia*, the geochemical stability of the repository site under increased temperature, and slow penetration of groundwater to the repository over a long period of time. This creates conditions for geochemical reactions between the contaminated water, rock and gases of the underground atmosphere (Pačes, 1987). In the course of millenia the groundwater flow may displace a large amount of material. These problems have no satisfactory solution so far.

The evaluation of sets of geological, hydrogeological and geophysical characteristics is used to produce a system of monitoring the changes in the groundwater body of the hydrogeological massif. This system is open, because separate boreholes and other observational objects are gradually included in it, provided they satisfy the basic conditions for monitoring the changes. These observations form an indispensable part of all activities related to constructing a repository, its exploitation and later closure.

The results of the hydrogeological analysis of the rock mass is the basis for constructing a deterministic mathematical model of the motion of fissure groundwater. Its purpose is the prediction of hydrological changes caused by constructing the repository, and determining the migration of substances from the massif to the neighbourhood. The monitoring data are used to improve the accuracy of the mathematical model.

(c) Geotechnical factors

Determining the mechanical properties of rocks of the hydrogeological massif are of hydrogeological importance. The observed values are used for the actual construction of the repository, as well as with regard to the disturbance of the rocks in the neighbourhood of the quarried spaces, which increase the water inflow into the underground workings. This is connected with the insulation of the workings

Table III. Hydrogeological rock mass characteristics for radioactive waste disposal and their estimation

Characteristic	Methods of testing	Aim of tests	Remark
Hydraulic conductivity k Transmissivity T	Steady-state - transient flow Pumping (inflow) tests (pumping and observation boreholes); recovery tests. Steep water-pressure injection tests; pressure fall-off tests; slug tests; transient pressure response tests (pulse test). Well-logging methods: thermometry; resistivity measurements; photometry. Geophysical methods: vertical electrical sounding. Loaded-body method.	Hydraulic parameters for estimation of rock mass Data for constructing prediction models of groundwater flow and contaminant transport. Dynamics of flow water in boreholes: filtration rate, vertical flow velocity, discharge into boreholes. Tentative hydraulic parameters of the rock mass (heterogeneity of the area).	$k = 10^{-9}\ \mathrm{m.s^{-1}}$ $T = 10^{-7}\ \mathrm{m^2.s^{-1}}$
Storativity S Hydraulic diffusivity a	Transient flow Pumping tests (pumping and observation boreholes).		$S_s = 10^{-6}\ \mathrm{m^{-1}}$ (specific resilient storativity)
Depth of groundwater level and its fluctuation	Groundwater level measurement in observation (monitoring) boreholes. Measurement of atmospheric precipitation. Geophysical methods: seismic refraction prospecting, vertical electrical sounding.	Monitoring groundwater extent and level changes in dependence on climatic, hydrological, seismic and anthropogenic effects.	Measurement frequency: once per day; water-level gauge, rain gauge (continually)
Groundwater flow	Single-well techniques; dilution method, pulse method; tracer tests. Loaded-body method.	Direction and velocity of groundwater flow. Water-bearing rock sorption characteristics.	
Age and origin of groundwater	Specific activity measurements of radiocarbon 14, tritium, helium 4; measurements of stable isotope contents of deuterium, oxygen 18, carbon 13, sulphur 34.	Retention time of infiltrated water, age and origin of groundwaters within rock mass; improvement of groundwater flow model.	Groundwater age limit 50,000 – 60,000 years
Coefficient of dispersion D_T, D_L	Tracer tests in common with loaded-body method and surface electrical prospection methods.	Migration parameters of rock mass for the spreading of contaminants.	

(continued)

Table III (continued)

Characteristic	Methods of testing	Aim of tests	Remark
Fracturing and porosity of collectors	Well-logging methods: resistivity, acoustic, seismic logging. Geophysical methods: seismic reflection prospecting, surface electrical resistivity profiling.	Charateristics of rock mass.	
Conductive fissured and fractured zones	Atmogeochemical prospecting; VLF method, infrared method (surface and airborne measurements).	As above	
Depth of bedrock	Geophysical methods: gravimetry, vertical electrical sounding, seismic refraction prospecting (well-logging method).	As above	
Thickness of Quaternary sediments and mantle rock	Geophysical methods: electrical resistivity methods, seismic refraction prospecting.	As above	
Hydrogeochemistry of groundwater	Complete chemical analysis of groundwater samples (gases, trace elements). Geophysical methods: electrical resistivity methods, method of spontaneous polarization; remote sensing.	Hydrochemical type of groundwater: a) for the construction of radioactive waste repositories; b) for the study of geochemical stability of rock mass; c) for the study of genesis of groundwater.	Groundwater non-agressive to concrete iron, etc.

walls with protective layers against the penetration of groundwater. The amount of water will not be large on a current basis, however, it is necessary to reckon with the time factor of the long-term effect of the water on the waste repository.

3. CONCLUSION

Radioactive waste disposal has become a topical problem in connection with the construction of nuclear power plants. The stability of repositories with respect to natural and anthropogenic effects must be considered in terms of millenia in view of the long-term toxicity of the waste being deposited. The selection of the repository site requires a comprehensive systemic approach characterized by the large volume of data and their subsequent analysis from various points of view. One of the limiting criteria is the detailed evaluation of hydrogeological factors.

The deep zone of a hydrogeological massif with a permeability of the order of 10^{-9} m . s^{-1} and less represents the most suitable medium for safe disposal of radioactive waste of all types, with regard to its long-term deposition, as well as the degree of migration of radioactive elements into the medium. The evaluation of the hydrogeological factors indicates that shallow surface repositories are unsuitable for disposing of highly and intermediately active waste. The apparent ease of constructing and monitoring repositories are insufficient guarantees against accidents which may occur as a result of unobservable destruction of the materials used over long periods of time. During the construction of the repository it is necessary to enhance supervision of technological discipline, which is not a negligible factor since it is difficult to monitor and check.

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HYDROGEOLOGICKÉ HODNOCENÍ BEZPEČNÉHO UKLÁDÁNÍ RADIOAKTIVNÍHO ODPADU

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Výstavba úložišť radioaktivního odpadu představuje specifický problém ve spojitosti s vyloučením negativních vlivů na ekosystém krajiny. V článku je proveden rozbor faktorů, které jsou rozhodující pro hydrogeologické hodnocení horninového masívu ve vztahu k bezpečnému ukládání radioaktivního odpadu. Specifičnost řešení je determinována dlouhodobou toxicitou odpadu. Výběr míst pro úložiště vyžaďuje komplexní systémový přístup. Jedním z rozhodujících a limitujících kritérií je hodnocení hydrogeologických faktorů.

Hloubková zóna hydrogeologického masívu s propustností řádu 10^{-9} m.s^{-1} a menší představuje nejvhodnější prostředí pro bezpečné ukládání radioaktivního odpadu všech typů. Z rozboru hydrogeologických podmínek vyplývá, že není vhodné ukládat radioaktivní odpady do povrchových úložišť.

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