

Estimation of Loading Density of Underground Well Repositories for Solid High-Level Radioactive Wastes

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Abstract—The convective transfer of radionuclides by subsurface water from a geological repository of solidified high-level radioactive wastes (HLW) is considered. The repository is a cluster of wells of large diameter with HLW disposed of in the lower portions of the wells. The safe distance between wells as a function of rock properties and parameters of well loading with wastes has been estimated from mathematical modeling. A maximum permissible concentration of radionuclides in subsurface water near the ground surface above the repository is regarded as a necessary condition of safety. The estimates obtained show that well repositories allow for a higher density of solid HLW disposal than shaft storage facilities. Advantages and disadvantages of both types of storage facilities are considered in order to estimate the prospects for their use for underground disposal of solid HLW.

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INTRODUCTION

The development of nuclear power production has resulted not only in increasing demand for raw materials, including uranium ore, but also in the necessity of processing and disposal of growing amounts of radwastes hazardous for the biosphere. Spent nuclear fuel (SNF) and liquid and solidified high-level radioactive wastes (HLW) left behind after SNF reprocessing at radiochemical plants are the most hazardous radwastes of the nuclear power industry. According to an IAEA estimate, the annual volume of radwastes of the world nuclear industry in 1987 was 14950 m³ of SNF and 2870 m³ of liquid and solidified concentrates of radiochemical plants (Laverov et al., 1991). There are no grounds to expect that the amount of radwastes will decrease significantly in the foreseeable future (*The Scientific...*, 1997).

In the passage of nuclear power engineering to the closed fuel cycle, the share of HLW in the total volume of radwastes will increase (Solonin, 2005). The disposal of solidified HLW in underground repositories at a depth of a few hundred meters is most advantageous in terms of environmental safety and economic expedience (Krauskopf, 1988; Laverov et al., 1991; *Disposition...*, 2001; *End Points...*, 2003). The transfer of radionuclides by subsurface water is the main mechanism of radioactive pollution of the geologic medium. The HLW produced at enterprises of radiochemical reprocessing of SNF initially are highly concentrated water solutions. To diminish the transfer of radionuclides from a repository to subsurface water, it is expedient to

convert liquid HLW into the solid state before disposal (Laverov et al., 1997). For this purpose, radionuclides of HLW are immobilized by a solid matrix that is intended to prevent removal of radionuclides while they are in contact with subsurface water. Additional insulation of HLW from subsurface water may be provided by placement of solidified radwastes in hermetic metallic containers enclosed in a buffering layer of low-permeability material with high sorption capacity with respect to radionuclides.

The protective properties of rocks that host a repository are important for reducing the rate of transfer of radionuclides reaching subsurface water through engineering barriers. These properties depend on the flow velocity of subsurface water and the sorption capacity of rocks with respect to radionuclides. To ensure a low flow velocity of subsurface water, repositories must be located in impermeable rocks devoid of faults and extended fractures. The rocks serve as a natural barrier that insulates HLW from the biosphere. Engineering barriers are relatively good insulation for HLW only at the initial stage of their storage. Further, despite relatively high stability of the solid matrix, chemical resistance and mechanical strength of the container, and high sorption capacity of the buffering layer, engineering barriers inevitably degrade, and the safety of disposal over the greater part of the storage time depends largely on the reliability of the geological barrier.

Underground repositories for disposal of solidified radwastes may be of shaft or well type, as well as specially reconditioned natural deep caves (St. John, 1982; Cooley et al., 1990; Kedrovsky, 1999; *Yucca Mountain...*, 2001). In shaft-type repositories, containers

with HLW are loaded into deep horizontal tunnels either directly or in special wells driven in walls or sunk in the bottoms of tunnels. In well repositories, placement of HLW-laden containers in the lower portions of deep wells having a large diameter and grouped into clusters is planned. To decrease removal of radionuclides into the biosphere along with subsurface water, the host rocks should be without faults and significant fractures. A shaft repository is a complex of underground workings within a large massif of undisturbed rocks. The search for such a massif is a complicated task, especially if the probability of faulting in the future is kept in mind. A repository in the form of a field of wells consists of separate holes as independent constructive elements, and each well requires a much smaller block of undisturbed rocks as a host. The lack of need for a large undisturbed rock massif, relatively simple construction, and low cost of building are substantial advantages of well repositories, which are currently considered to be a promising variant of underground disposal of radwastes (Smellie, 2004). The choice of one or another type of disposal is a complicated problem, the solution of which depends on many factors, including technical and economic feasibility and social and political aspects.

One of the most important parameters characterizing the efficiency of use of a territory assigned for a repository is the permissible density of loading of the territory with wastes. This parameter is the ratio of the HLW mass that may be safely disposed of in the underground repository to the area of the territory assigned for this purpose. A method of estimation of this parameter for a well repository as a variable depending on the properties of HLW and host rocks is considered below. The estimates obtained are used for comparison of well and shaft repositories.

STATEMENT OF THE PROBLEM

Radionuclides migrate in the geologic medium mainly owing to their transfer by subsurface water. The subsurface water flow consists of two components: the regional (forced) flow caused by topographic heterogeneities and the free convective flow driven by differences in water density controlled by spatial variation in salinity or temperature.

One of the necessary conditions constraining a site chosen for an underground HLW repository is a low velocity of the regional flow. However, it should be taken into account that the ongoing radioactive decay in HLW loaded into a repository leads to considerable heat release (Roglans-Ribas and Spinrad, 1989; Rybal'chenko et al., 1994). As a result, the rocks near the repository are heated and the subsurface water here acquires a higher temperature. Thus, the subsurface water here becomes lighter than at a distance from the repository, and this difference is a driving force for ascending thermoconvective currents near the loaded portion of the repository (Fig. 1). The radionuclides

supplied from HLW into subsurface water may be transferred by these currents toward the surface. While the velocity of the regional flow is low, the thermoconvective transport of radionuclides is among the main factors controlling the reliability of the geological barrier and the hazard of removal of radionuclides from the repository into the biosphere.

The spreading of radioactive pollution along with subsurface water may remain hazardous for the biosphere for hundreds and even thousands of years. Hence, the only reliable way to estimate the supply of radionuclides from a repository to the biosphere is a forecast based on the results of mathematical modeling. Such a forecast makes it possible to establish the distribution of radionuclides in subsurface water above an HLW repository. Immediately after HLW disposal in a repository, at the initial moment t_0 , the radionuclide concentration equals zero because the host rocks are still unheated and thermoconvective currents are not developed. Thus, even if the engineering barriers have been destroyed by this moment, radionuclides cannot get to the surface. Further, the rocks near the loaded portions of wells are gradually heated and ascending branches of thermal convection transport radionuclides contained in subsurface water toward the surface. From this moment, the radionuclide concentration in near-surface water begins to differ from zero and grows over a certain time interval. However, owing to the ongoing radioactive decay, the concentration of radionuclides in HLW drops, and the amount of radionuclides supplied to subsurface water decreases as well. At the same time, the heat release in HLW decreases, as a result of which the concentration of radionuclides in water at the contact with HLW and the velocity of the thermoconvective flow also decrease. From a certain moment t_{extr} , the concentration of radionuclides in near-surface water begins to drop, tending to zero at infinitely increasing time t . Thus, at $t = t_{extr}$, the radionuclide concentration in subsurface water reaches a maximum C_{max} . Because at this moment the HLW repository poses the highest environmental hazard for the biosphere, the C_{max} value may be used as a quantitative index of repository safety. An HLW repository may be classified as safe if C_{max} for each radionuclide contained in HLW does not exceed its maximum permissible concentration.

It is evident that C_{max} is lower the more reliable the engineering barriers of the repository are. However, the geological barrier is crucial over the main period of HLW disposal, and C_{max} may be estimated approximately assuming that engineering barriers, e.g., the container and buffering layer, were destroyed at the moment of HLW disposal in the repository. The safe HLW disposal estimated on the basis of this assumption corresponds to excess reliability of HLW insulation from the biosphere.

The C_{max} value also depends on the permeability of host rocks (k) and the parameters of the repository laden with radwastes, including the linear density of

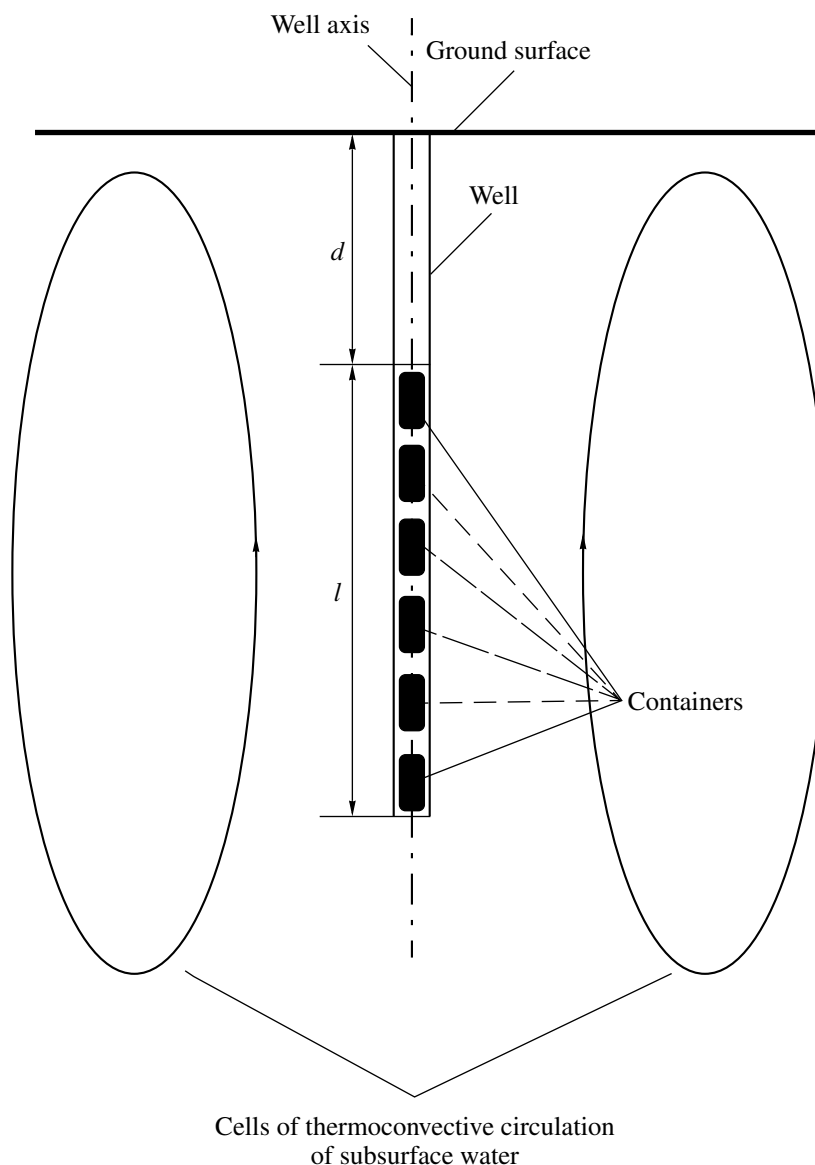


Fig. 1. Thermoconvective transfer of radionuclides from HLW-laden containers disposed of in the lower portion of a large-diameter well: a conceptual scheme. d , distance from the ground surface to the uppermost container; l , length of the loaded well portion.

heat release (M) per unit length of the loaded portion of well at the initial moment, the length of the loaded portion (l), the distance of the loaded portion of the well to the surface (d), and the half-distance between adjacent wells (h). Mathematical modeling allows calculation of the function

$$C_{\max} = C_{\max}(k, M, l, d, h). \quad (1)$$

The case of a single-well repository corresponds to the maximum value of $C_{\max}$ at $h \rightarrow \infty$. A mathematical model of thermoconvective removal of radionuclides from a single well was described by Malkovsky et al. (1994). The model assumes that the integrity of containers and the buffering layer is destroyed from the moment of HLW disposal in the well and solidified HLW interacts with subsurface water from the very

beginning. Computations performed on the basis of this model show that the safety of HLW disposal may be ensured at technically feasible and economically realistic parameters. For example, at $k = 10^{-15} \text{ m}^2$, $l = 1 \text{ km}$, and $M = 504 \text{ W/m}$ (Wang et al., 1989), this corresponds to the disposal of one container every 4 m of the HLW-laden well segment. However, it should be kept in mind that different programs deal with containers of distinct construction, size, and mass of contained HLW. Under the above conditions, the safety of HLW disposal in a single well is ensured at d of a few hundred meters. The computation does not take into account delay of radionuclides owing to their sorption on host rocks and chemical interaction with rocks. In the case of colloidal forms of radionuclide transport, the protective proper-

ties of rocks, i.e., delay of radionuclide migration by sorption, may be less efficient than the sorption of radionuclide species dissolved in subsurface water (Smith and Degueudre, 1993; Ryan and Elimelech, 1996; Kersting et al., 1999).

As was mentioned above, the efficient use of a repository requires placing wastes in a cluster of wells rather than in a single well. In this case, thermoconvective currents develop near the loaded portion of each well. The interaction of these currents may reinforce the resultant ascending currents, and the rate of radionuclide migration from the wastes disposed in wells toward the surface may markedly increase in comparison with a single well. Thus, the well must be located at a rather great distance from one another so that the interaction of thermoconvective flows may be neglected. However, the shorter this distance, the more efficiently it is possible to use the repository territory.

Let us introduce a quantitative parameter of the interaction between the convective currents pertaining to each well. Because the practical implication of this interaction is related to the increase in removal of radionuclides to the surface, it is reasonable to use the ratio

$$R = \frac{C_{\max}(M, d, l, h)}{C_{\max}(M, d, l, h \rightarrow \infty)}$$

for this purpose.

The above parameter is the ratio of $C_{\max}$ at a certain $2h$ to $C_{\max}$ of a single well. The closer R is to unity, the less the resultant removal of radionuclides to the ground surface. It is evident that $R \rightarrow 1$ at $h \rightarrow \infty$. Hence, the greater h , the higher the safety of the repository. However, the less h , the more efficient the use of the repository. Thus, the problem is reduced to the computation of the minimum h value at which R remains close to unity.

From a practical viewpoint, it may be accepted that the interaction of convective flows near particular wells is insignificant if $R - 1$ is less than a threshold limit of 10–20%. This limit has been chosen based on the following reasons. The computation of removal of radionuclides from a repository is based on parameters that characterize the properties of subsurface water, host rocks, and the disposed wastes, including the density and the depth of their disposal near the well bottom. The permeability of rocks, which depends on the permeability of the crystalline matrix and the fracturing of rocks, is estimated with the least accuracy. Thus, the uncertainty in the estimation of permeability cannot be less than errors in the determination of lattice permeability, which commonly reach 10–13% (Shmonov et al., 2002).

MODELING RESULTS

The rates of thermal convection of subsurface water, temperatures, and concentrations of radionuclides near a single well are distributed symmetrically relative to

the well axis. The axial, or cylindrical, symmetry of the problem substantially simplifies modeling. In the case of several wells, the symmetry is destroyed. Therefore, in mathematical terms, the modeling of thermoconvective transfer of radionuclides by subsurface water in the case of several wells is a more complicated problem than in the case of a single well. A mathematical model that takes into account the mutual effects of thermal convection near neighboring wells and a description of calculations in the framework of this model were given by Malkovsky et al. (1995).

The parameter d in (1) equals the minimum distance that radionuclides pass moving from the loaded portion of the well to the ground surface. This parameter largely affects the intensity of thermoconvective removal of radionuclides from particular wells. Hence, the effect of d upon R , characterizing the interaction of wells, should be not great. The parameter l is a geometric measure of the thermoconvective flow near each well. According to similarity theory (Kutateladze, 1982), R depends on l as a function of h/l . Thus, in a general case, it is sufficient to analyze the relations of R to M , k , and h in order to estimate the interaction of thermoconvective flows near adjacent wells in quantitative terms. The relationship $R(M, k, h)$ obtained from computer modeling and described by Malkovsky et al. (1995) is shown in Fig. 2. It may be noted that R monotonically decreases with growing h , asymptotically approaching unity at $h \rightarrow \infty$, and increases with growth of M and k .

Consider the parameters of the system that correspond to curve 1 in Fig. 2. A permeability of 10^{-16} m^2 is typical of crystalline rocks having poorly developed fractures and located beyond fault zones. $M = 504 \text{ W/m}$ corresponds to the initial linear density of heat release when one container is disposed of in each 4 m of the loaded well portion (Wang et al., 1989). It should be noted that, at $h \geq 50 \text{ m}$ and at parameters of the system that fit curve 1 in Fig. 2, $R - 1$ is relatively low. Thus, if the results are interpreted in terms of safety measured by $C_{\max}$, this implies that, at a distance of more than 100 m between wells, the convective transfer processes near adjacent wells may be accepted as practically independent processes (at $M = 500 \text{ W/m}$ and $k = 10^{-16} \text{ m}^2$).

At a higher permeability of rocks and density of well loading with wastes (Fig. 2, curves 2, 3), the effects of interaction of convective flows pertaining to particular wells may be significant at much greater h . However, it should be kept in mind that a low permeability of rocks is one of the necessary conditions of a site assigned for a repository and a case where k is much lower than 10^{-16} m^2 is not realistic. Rather severe limitations are imposed on the level of heat release from disposed wastes. It is suggested that, before final disposal, radwastes should be stored for a long time in transient repositories, where the rate of heat release drops relatively rapidly (Wang et al., 1989; Rybal'chenko et al., 1994). Thus, in practice, M cannot

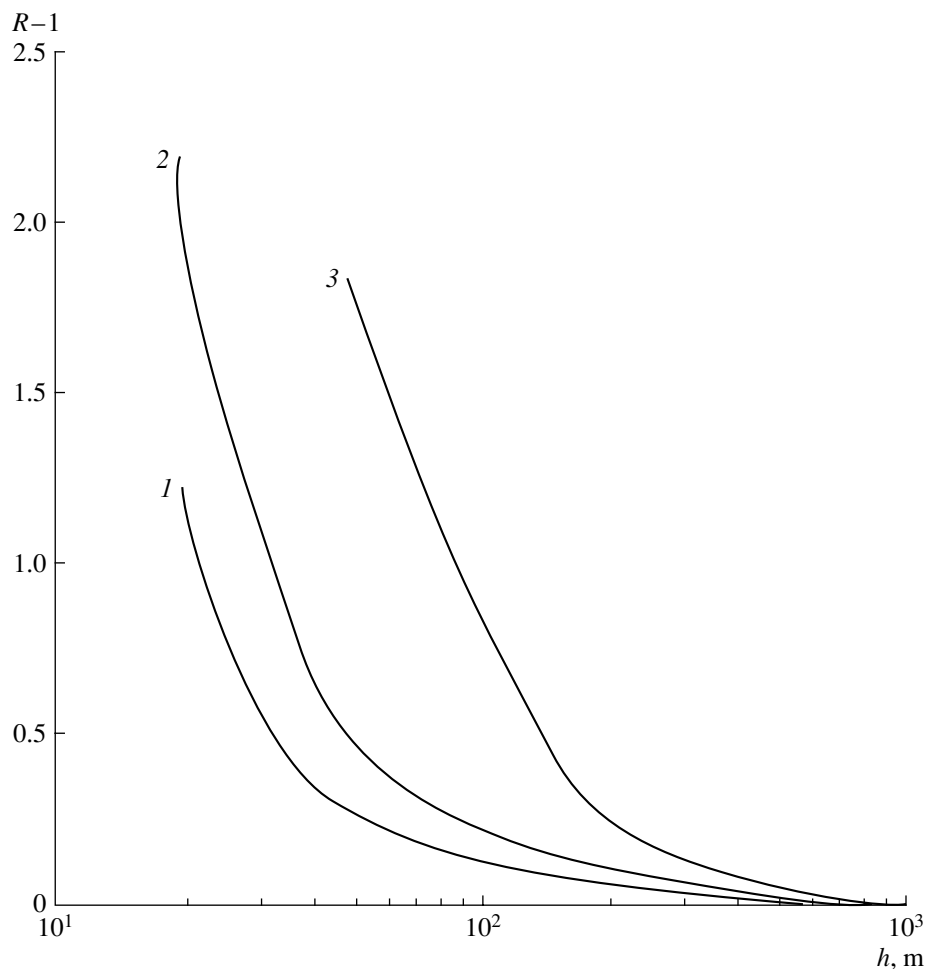


Fig. 2. Effect of well spacing on the increase in removal of radionuclides owing to interaction of thermoconvective flows near adjacent wells ($l = 500$ m, $d = 500$ m). (1) $M = 500$ W/m, $k = 10^{-16}$ m²; (2) $M = 1000$ W/m, $k = 10^{-16}$ m²; (3) $M = 500$ W/m, $k = 10^{-15}$ m².

markedly exceed the value of 500 W/m used in the computation.

DISCUSSION

The computations show that, if wells are located in poorly fractured rocks with a permeability of $\sim 10^{-16}$ m² and the density of HLW disposal in the loaded portions of wells provides a heat release of ~ 500 W/m, the mutual effects of neighboring wells do not appreciably increase the removal of radionuclides to the ground surface if a distance between adjacent wells is less than 100 m. It is expedient to compare the density of waste disposal in well and shaft HLW repositories. As has been shown above, in the considered range of parameters, the spacing of wells at a distance of 100 m from one another may be regarded as a safe with respect to leakage of radionuclides.

In the design of a shaft repository (Kedrovsky, 1999), HLW-laden containers are placed in horizontal workings at a depth of about 500 m and at a distance of 50–100 m from one another. According to Malkovsky

et al. (1994), a depth of 500 m is also sufficient for well repositories. Because a great number of containers may be disposed of in each well, for wells spaced at ~ 100 m, the loading density of the territory of a well repository is much higher than that of a shaft repository, as may be illustrated by a simple calculation.

According to one design of a shaft repository (Kedrovsky, 1999), HLW-laden containers are placed in horizontal tunnels at a depth of ~ 500 m. Each of ten tunnels spaced at 100 m is approximately 500 m long. Let us assume that the density of filling, i.e., the number of containers per unit length, of both tunnels and wells is the same. In one of the possible variants, the length of a container is 5 m (Kedrovsky, 1999). Assume that a container is placed every 10 m in both the tunnel and the well. In this case, 50 containers will be disposed of in each tunnel and 500 containers, in the repository as a whole. The total area of such a repository (without auxiliary sites and a protective sanitary zone) is equal to $\sim 45 \times 10^4$ m². If the safe distance between adjacent wells is 100 m, 60 wells can be located in the same area in a regular square pattern. As in the above calculation,

assume that these wells are 1 km deep and the upper edges of their loaded portions are located at a depth of 500 m. In this case, 50 containers can be placed into each well (3000 containers in total). Thus, in the same area, a well repository stores six times more wastes in comparison with a shaft repository. It is evident that the same proportion will be retained at any number of tunnels in a shaft repository at the accepted distances between tunnels and wells.

At first glance, it seems that the obtained estimate requires a correction related to the method applied to determination of the safe distance between neighboring wells. For two adjacent wells, a distance between them is assumed to be safe if $R - 1$ does not exceed a threshold of 10–20%. If the square well pattern is regular, each well has four neighbors, or three if the well occurs at the site boundary. Hence, the total disturbing effect of adjacent wells may augment $C_{\max}$ by 40–80%. Such augmentation is substantial, but, in estimating its implications, the following circumstance should be taken into account. Calculations performed previously (Malkovsky et al., 1994) showed that, in the case of removal of radionuclides from a single well, $C_{\max}$ decreases by an order of magnitude with an increase in d by 40–50 m. Thus, the increase in $C_{\max}$ may be compensated by an increase in d by 14 m.

Other advantages of well repositories are the lack of a need to search for extensive blocks of undisturbed rock because each well may be located in a relatively small block of poorly fractured rock, the technological simplicity of construction, and the relatively low cost of building and exploitation.

The blocks of poorly fractured rocks for disposition of particular wells may be chosen from the results of on-land geophysical surveying (Ogil'vi, 1990). In comparing different types of underground repositories for radwastes, it should be kept in mind that the mining works carried out during their building may disrupt the rocks at the chosen site. The drilling of wells provokes lesser disturbances than the driving of tunnels in shaft repositories. Because the wells are vertical, the probability that a newly formed fracture or fault will extend through a well is lower than that for a horizontal tunnel in a shaft repository. Furthermore, wells are unconnected elements of a repository, whereas a shaft repository is a complex of connected structures. Therefore, the damage to a shaft repository caused by tectonic disturbances would be much greater than that to a well repository.

In general, the advantages listed above demonstrate that well repositories are preferable in technical and economic terms. At the same time, access to particular HLW-laden containers disposed of in a well repository is hampered, and, because of this, it is difficult to monitor the status of loaded zones in wells and remove some or all HLW-laden containers if necessary. This shortcoming of well repositories requires special attention because there is as yet no experience in under-

ground disposal of solid HLW on an industrial scale in world practice. Therefore, some questions pertaining to the safety of underground repositories remain open. In particular, it is necessary to carry out special field experiments on the long-range stability of engineering barriers, to study the transport properties of rock massifs influenced by large-scale thermal perturbations, and to assess the implications of colloidal transfer for spreading of radioactive pollution by subsurface waters.

A lack of information on these effects may lead to erroneous estimations of the safety of designed underground repositories for solid HLW. Such unexpected effects may lead to contamination of the biosphere with radionuclides. Therefore, at the stage of construction of pilot industrial underground HLW storage facilities, the status of the repository and host rocks should be carefully monitored, with the possibility of partial or complete removal of HLW-laden containers being retained. It is precisely for this reason that most national programs are oriented to the building of shaft repositories (McCombie et al., 1993; *Yucca Mountain...*, 2001; Choi, 2005). In the future, with the acquisition of additional experimental data on the underground disposal of solid HLW, the reliability of safety estimates will be increased. The requirements for monitoring of and immediate access to disposed wastes will less severe, and the more favorable technical and economic attributes of well repositories will become crucial in the choice of repository type.

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