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Using the Recharge Area Concept as a strategy for siting underground nuclear waste repositories

Az utánpótlódási terület koncepció (Recharge Area Concept) stratégiai alkalmazása felszín alatti radioaktív hulladéktároló kutatásában

Grant SHENG[1] – József TÓTH[2]

(2 Figures, 2 Tables)

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Tárgyszavak: radioaktív hulladék, földtani elhelyezés, talajvíz, utánpótlódás, megcsapolás, hulladéktároló, hidrogeológiai modellezés

Abstract

The Recharge Area Concept is the proposition that in Canadian-Shield type natural environments recharge areas of regional groundwater flow systems are superior for high-level nuclear waste repositories to other types of groundwater flow regimes, especially to areas of groundwater discharge. This conclusion is reached from an analysis of basinal groundwater flow models. The calculations were made for a two-dimensional flank of a fully saturated topographic basin, 20 km long and 4 km deep, in which groundwater is driven by gravity. Variants of hydraulic-conductivity distributions were considered: 1) homogeneous; 2) stratified; and 3) stratified-faulted. The faults attitudes were changed by steps from vertical to horizontal for different variants. The model is assumed conceptually to represent the crystalline-rock environment of the Canadian Shield.

The hydrogeologic performances of hypothetical repositories placed 500 m deep in the recharge and discharge areas were characterized by thirteen parameters. The principal advantages of recharge- over discharge-area locations are: 1) longer travel paths and return-flow times from repository to surface; 2) robustness of predicted values of performance parameters; 3) field-verifiability of favourable hydrogeologic conditions (amounting to an implicit validation of the calculated minimum values of return-flow times); 4) site acceptance based on quantifiable and observable flow-controlling parameters; and 5) simple logistics and favourable economics of site selection and screening. As a by-product of modelling, it is demonstrated that the presence of old water is not an indication of stagnancy.

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[1] Faculty of Environmental Studies, York University, 4700 Keele Street,Toronto, Ontario, M3J 1P3, Canada

[2] Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, T6G 2E3, Canada

Összefoglalás

Az utánpótlódási terület koncepció (Recharge Area Concept) lényege az, hogy a Kanadai pajzs típusú természetes környezetekben a regionális felszín alatti vízáramlási rendszerek utánpótlódási területei alkalmasabbak nagy radioaktivitású hulladéktároló kiépítésére más típusú felszín alatti vízrendszereknél, különösen a megcsapolási területeknél. Erre a következtetésre a medence méretű vízáramlási modellek elemzéséből juthatunk. A számításokat egy 20 km hosszú, 4 km mély topográfiai medence tökéletesen telített kétdimenziós szelvényére végeztük el, ahol a talajvizet a gravitáció mozgatja. A következő vízvezetőképesség-eloszlási eseteket vettük figyelembe: 1) homogén; 2) rétegzett; 3) rétegzett és töréses. A vetők helyzetét a különböző esetekre lépésenként változtattuk a függőlegestől a vízszintesig. A modellbe koncepcionálisan a Kanadai Pajzs kristályos kőzetekből álló környezetét építettük be. Az utánpótlódási és megcsapolási területeken 500 m mélységben elhelyezett képzeletbeli tárolók hidrogeológiáját tizenhárom paraméterrel jellemeztük. Az utánpótlódási területen lévő tároló leglényegesebb előnyei a megcsapolásihoz képest: 1) hosszabb vándorlási útvonalak és elérési idők a tárolótól a felszínig; 2) sokkal jobb várható paraméterértékek; 3) a kedvező hidrogeológiai feltételek terepi ellenőrizhetősége (ami az elérési idők számított minimum értékeinek egyértelműsítéséhez vezet); 4) a telephelynek a mennyiségileg meghatározható és észlelhető áramlási paramétereken alapuló elfogadása; valamint 5) a telephely kiválasztás és szűrés átlátható logisztikája és a kedvező gazdasági feltételek. A modellezés melléktermékeként az is kiderült, hogy az idős vizek jelenléte nem utal az áramlás hiányára.

Introduction

The general concept of nuclear waste disposal

The idea of permanent disposal of high-level nuclear waste (HLW) in terrestrial geologic media was extant from at least 1957 (National Research Council, 1957). Since the first international meeting held over 35 years ago (IAEA, 1960), there has been a tremendous amount of R&D (research & development) work done towards solving this problem. The general concept adopted internationally (e.g. Belgium, Canada, Finland, France, Germany, Holland, Japan, Spain, Sweden, Switzerland, UK, USA, etc.) involves the burial of radioactive wastes in underground repositories to be built approximately 500–1000 m deep in some stable, terrestrial geologic media with the addition of various engineered barriers to enhance further the confinement of contaminants (SHENG et al. 1993a; SHEMILT & SHENG, 1983). The existing international consensus on the practicability and efficacy of this general approach is typified by the „collective opinion" of the Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA), the International Atomic Energy Agency (IAEA) and the Commission for European Communities (NEA/IAEA/CEC, 1991).

Technical issues

Since the overriding concerns of this disposal endeavour are to ensure safety of humans and protection of the environment both now and far into the future, a convincing demonstration of the safety of the disposal system primarily involves technical issues. The first is associated with the capability to make forecasts of far-future events (especially those geologically related), and the second, with the extent that such forecasts can be „confirmed" in some fashion within the obvious limits of our present time. However, the methodology as presently envisaged to implement the general concept faces some inherent difficulties in addressing these technical issues. These difficulties stem from the peculiarities of the disposal technology which is distinguished by at least two unique characteristics: (a) the very long time spans (tens-, or even hundreds-of-thousands of years) over which the disposal system must remain effective and, (b) no precedents exist for such an endeavour.

The geologic issue

With respect to the first technical issue, much effort and resources have been devoted by the international community to geologic and geotechnical R&D work because of the concept's heavy reliance on the geology to act as a natural barrier (SHEMILT & SHENG 1983; SHENG et al. 1993a). It is axiomatic to view groundwater always as the negative agent that transports contaminants to the surface, and fractures as the conduits through which the groundwater does the transport. These assumptions stem from an implicit world-view that we must somehow create a „water-tight box" to confine the contaminants. Although there is acknowledgement that absolute confinement may not be possible, it is, nevertheless, the idealized goal, as indicated by use of terms such as „waste isolation", „multi-barriers", etc. The „box" is to be made „water-tight" with a series of man-made (container, buffer, backfill, vault) and natural barriers (host geologic medium, and associated features). Thus, the major research effort internationally is directly or indirectly focused on how to keep groundwater (a) from intruding into the vault, (b) away from the waste, (c) from exiting the vault, (d) away from fractures; and (e) studying the influence of fracture and fracture-associated phenomena on the movement of groundwater. Both (d) and (e) have been, and continue to be, the main focus of R&D work under the present vision of waste disposal.

However, many years of intense research documented in publications such as GEOVAL (1987, 1990) have shown the great difficulties associated with items (d) and (e). There are at least two underlying factors that give rise to this situation: (1) an inherent characteristic of fractures is that they are essentially „discontinuous" on the scale relevant to site characterization and, (2) although various theories exist to explain the formation and propagation of fractures, the phenomenon is so complex that accurate predictions or forecasting of their future behaviour, even in the short-term, is not yet within the realm of our present understanding and technology. Furthermore, as pointed out in SHENG et al. (1993a), even if it were possible to do such accurate predictions and characterizations, there is no guarantee that new fractures will not form during the time period that the disposal vault is required to remain effective. These are but several of the most salient and fundamental issues that the current disposal concept have yet to resolve.

The validation issue

With respect to the second technical issue, the extent with which the forecasts from models can be confirmed (or to use the popular term in this field: „validated") obviously has a great bearing on the degree of confidence one places on the models and their results. However, demonstration of the safety of the disposal system is problematical in this situation where the ultimate performance of the system at some distant point in the future cannot be ascertained. Adequate/satisfactory performance must be inferred based on a combination of: (a) our present understanding of natural processes, (b) knowledge about relevant system parameters, (c) our ability to design, and have confidence in, the engineered systems and (d) our ability to extrapolate this collection of knowledge far into the future.

Computerized simulation is the only means we have to carry out systematically and quantitatively such an extrapolation upon which to base an inference of satisfactory system performance so far into the future. While this paper presents the results of such a simulation study, the specifics of validating the underlying model must be dealt with in detail in another paper in accordance with a framework proposed by SHENG et al. (1993b).

The „Recharge Area Concept" – (RAC)

In response to the challenges posed by these two issues, a new approach towards demonstrating safety performance called the Recharge Area Concept (RAC) has been proposed by TÓTH & SHENG (1996). Starting at the most fundamental level, the philosophical basis of this new approach is markedly different from that of the present waste isolation methodology. Rather than placing the emphasis on engineering „active" barriers (i.e., containers, buffers, backfills, etc. to isolate the waste) or avoidance of fractures in the geologic medium to confine or retard contaminant movement, the RAC approach relies on a natural fundamental force (gravity) to do the job in a „passive" fashion. By exploiting knowledge about regional groundwater flow patterns, one can strategically locate a repository at the recharge of a regional flow system so that escaping contaminants would be carried by water downwards deeper into the earth where they may be trapped in stagnant zones (areas of no-flow) or be transported along a very long flow trajectory during which time radioactive decay would render the radionuclides harmless, if and when, they do ever surface. In this approach, we assume that the repository will fail (i.e., leak contaminants) at some time in the future. Thus the RAC is a passive „safe-fail" system as opposed to the type of active „fail-safe" systems being developed internationally. Moreover, the adoption of the RAC as a siting strategy adds many other safety features and ultimately confers additional significant margins of safety to the disposal system as compared to the existing general disposal concept.

Premise for development of RAC

The Recharge Area Concept is developed from two basic arguments. First, it is recognized that the favourable combination of maximum groundwater flow-path lengths with minimum flow velocities, ensuring maximum travel times and maximum dilution of contaminants, is most likely to occur along flow lines that originate in regional recharge areas. Second, for recharge positions it appears possible to confirm calculated travel times, i.e. to confirm model calculations to the extent needed for the guaranteed safety of a repository. The second point implies the assertion that minimum travel times can be established which cannot possibly be negated by unknown deviations from assumed geologic conditions such as, for instance, undetected fractures or fault zones. Such an assurance cannot, on the other hand, be given for other basinal areas, including those of groundwater discharge. Furthermore, adoption of the RAC as a guiding principle facilitates and rationalizes the practical procedural aspects of the selection, screening and evaluation of a repository location. Although economy and logistical ease are not specifically considered in this paper, the great advantages conferred in these respects by a siting strategy based on the RAC should not be ignored.

Assumptions of the RAC

The following are assumptions underlying the RAC:

1) the RAC does not purport to predict the groundwater travel time (i.e. when the groundwater will re-surface at the discharge zone). It merely places a bound on the fastest time that the groundwater can possibly re-surface (hence „minimum travel time");

2) the system only delays the escape of contaminants to the surface and does not necessarily confine them within the vault or the geosphere (i.e. the repository is assumed to fail sometime in the future);

3) the only significant medium for the transport of contaminants is the groundwater;

4) the contaminants cannot travel faster than the water „front" - i.e. the leading edge of the transport medium;

5) the geologic medium in which the groundwater flows is saturated;

6) the RAC does not assume constant hydraulic conductivity of the geologic medium, nor constant fluid density with depth. (Although variations in values of these parameters can affect the "shape" of flow patterns, such as the idealized representations shown in *Figures 1* and 2, they do not alter the general direction and other manifestations of the flow patterns.)

Demonstration of safety performance

As discussed in SHENG et al. (1993b) and CASWELL (1976) the most important element in the process of validating a model is to have a clear understanding, and to provide a precise statement, in operational terms, of what the goal of the

Figure 1.

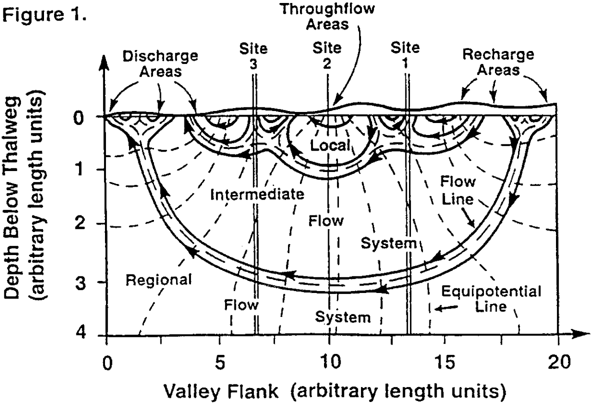

Fig. 1 Distribution of flow, hydraulic heads, and principal hydraulic regions in drainage basins with sinusoidally undulating water table superimposed on a linear regional slope (Composite Basin) (from TÓTH & SHENG 1996, Figure 1, p. 6)

1. ábra. A vízáramlás, a hidraulikus emelkedési magasságok és az elsődleges hidraulikai rezsimterületek eloszlása olyan vízgyűjtő medencében, ahol a talajvízfelszínt egy lineáris lejtő és egy színuszos hullámzás összege írja le (összetett medence)

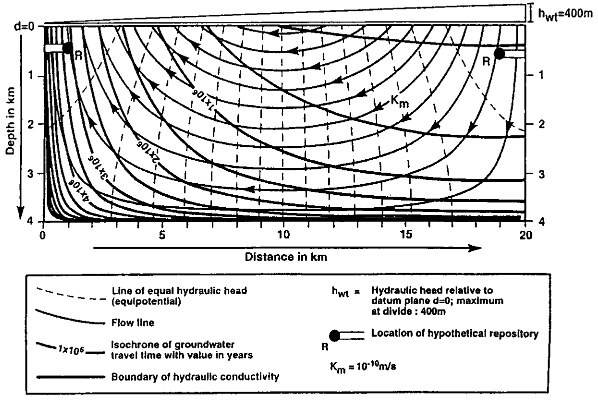

Fig. 2 Calculated distributions of hydraulic heads, groundwater flows lines, and isochrones of groundwater travel-time between water divide and valley bottom, in a basin of homogeneous matrix hydraulic conductivity (from TÓTH & SHENG 1996, Fig. 3, p. 11)

2. ábra. A hidraulikus emelkedési magasságok, felszínalatti vízáramvonalak és a vízválasztó és a völgy közötti áramlási idő izokronjainak számított eloszlása olyan medencében, melyben a mátrix hidraulikus vezetőképessége homogén eloszlású model is. In this present example, the application of the RAC to repository siting, the goal is to demonstrate the safety performance of the disposal system by calculating a „minimum travel time" (MTT) for the contaminated groundwater to reach the surface. The MTT is the shortest (or equivalently, the fastest) time that the groundwater can possibly re-surface at the discharge zone. It is calculated based on an estimation of the shortest path length that the water can take from the repository to the surface in a regional groundwater flow system. The flow distribution and other associated characteristics of groundwater in such a system can be derived from the surface topography by applying the fundamental principle of groundwater flow as first elucidated by TÓTH (1963).

The MTT derived from a particular set of topographic and subsurface geologic conditions can, in the first instance, be compared with the half-life of any specific radionuclide of concern. Should the MTT be significantly greater than the half-life of a particular radionuclide (say ten times) then clearly that radionuclide can be deemed to pose no potential harm in the future. Should the half-life be greater than the MTT, then the maximum amount of the radionuclide that can possibly reach the surface can be calculated based on its initial inventory in the repository together with its half-life. The maximum possible dose from such a radionuclide can be calculated by estimating its concentration at the point of discharge at the surface. The surface area needed to estimate the concentration is upwardly bounded by the lateral extent of the discharge area which can be estimated from the particular set of topographic and subsurface geologic conditions used in the simulation study or, alternatively, based on actual measurements if a specific site is being investigated. The estimated dose figure can then be compared with the regulatory limit to decide if a particular hypothetical or actual site is safe.

General approach to repository siting based on the RAC

The practical approach to achieve the ultimate objective of safe waste disposal by employing the RAC may be summarized in the following seven basic steps:

1) Selection of a repository location from which groundwater travel times to prohibited points are assumed (from general considerations, experience and/or scoping calculations) to be sufficiently large.

2) Calculation of possible travel times by site-specific models of regional groundwater flow.

3) Calculation of measurable fluid-dynamic parameters of the groundwater flow regime.

4) Installation of exploratory instrumentation at key points in the basin.

5) Verification of the appropriateness (i.e. applicability) of the model by comparing the calculated fluid-dynamic parameters with their field determined values.

6) Acceptance/rejection of the model, depending on the degree of agreement between calculated and observed values of the dynamic parameters.

7a) If model is rejected, construction of new one and repeating of the process from Step 3.

7b) If model is accepted, acceptance/rejection of site based on a comparison of the calculated minimum travel times with the required minimum travel time.

Basic principles, concepts and procedures needed in the execution of the above seven steps, as well as considerations in support of the Recharge Area Concept, are briefly presented in the following sections.

Regional groundwater flow and its characterization

The spatial and temporal distributions, the fluid dynamic properties and the wide array of natural manifestations, i.e. the general characteristics of gravity-induced regional groundwater flow have been studied extensively over the last three decades (TÓTH 1963, 1984; BREDEHOFT et al. 1982). Also, these issues are routinely treated in modern texts on hydrogeology (e.g. FREEZE & CHERRY 1979). For the present purposes it is necessary to review briefly only those characteristics which are directly relevant to the problem of nuclear waste disposal in the Canadian Shield.

Groundwater Flow Systems: areas of recharge, discharge and throughflow

Groundwater flow in the Canadian Shield is generally recognized to be driven by gravity, i.e. by elevation differences of the water table. The flow is regionally unconfined, that is, a change anywhere in the water table entails an adjustment of the flow pattern throughout the entire domain. In regionally unconfined gravity-flow fields, groundwater can be at rest only in the idealized situation where the upper surface of the water body, namely the water table, is horizontal and infinite in areal extent. In real conditions, however, as in the Canadian Shield, the configuration of the water table is a close replica of the topographic relief. In such cases, groundwater moves downward, or away from the water table, under topographically high regions; it moves upward, or toward the water table, beneath topographically low areas as, for instance, stream valleys or lake basins; and flow is parallel to the water table under medium elevations between mounds and vales. Based on their distinct functions in the subsurface hydrology of drainage basins these three different regions of groundwater hydraulics are termed, respectively, as recharge-, discharge- and throughflow-, or midline-, areas of groundwater (*Fig. 1*).

A family of flow lines originating in a given recharge area and terminating in a given discharge area is referred to as a groundwater flow-system. Flow systems terminating in discharge areas which are immediately adjacent to their recharge areas are called local systems, whereas the systems connecting the principal recharge areas with the principal discharge areas of a topographic basin are termed regional (*Fig. 1*). Intermediate systems may straddle one or more local systems without, however, extending from the principal watershed to the main valley. In basins with complex groundwater flow patterns (e.g., Fig. 1), different hydraulic regions of local and higher order flow systems may spatially coincide. At Site 2, for example, the discharge area of a local system is superimposed on the descending limb, i.e. recharge portion, of the regional system, whereas at Site 3 local recharge is underlain by the regional discharge area.

Additional complications may be introduced into the pattern of basinal groundwater flow by permeability variations. The effects on the flow patterns of heterogeneities, such as fault zones and fractures, depend on their degree, areal extent, orientation with respect to flow lines, and elevation of outcrop regions.

Comparison of key characteristics of regional groundwater flow regimes

Flow in recharge vs. discharge areas

The two basic arguments upon which the RAC has been developed, as stated earlier, are: 1) that a position in a regional recharge area ensures the maximum degree of dilution and maximum possible travel times back to the land surface (as compared with other positions in a basin of similar hydrogeologic properties) for contaminants possibly escaping from a repository, and 2) that it is recharge environments where the groundwater flow-characteristics are sufficiently insensitive to discrepancies between actual hydrogeologic conditions and conditions assumed for purposes of calculations, to allow the construction of adequately robust flow models and their validation. Clearly, the above reasoning is relativistic: it compares the effects of different positions in topographically defined drainage basins on those hydrogeologic attributes which play a role in regional groundwater flow. The greatest contrasts in the basinal scale hydrogeologic attributes can be expected to exist between regional recharge and discharge areas, which represent opposite end-members of basinal flow- and transport-conditions (TÓTH 1984). It is logical, therefore, that a comparison between the relevant key characteristics of regional groundwater low in recharge-and discharge-areas should provide an adequate test of the validity of the above arguments and, thus, of the Recharge Area Concept.

Model calculations

The following sections briefly describe a modelling study which demonstrates the advantages of locating an underground repository in a regional recharge zone. Full details about the model, parameters, and results are given in TÓTH & SHENG (1996).

Scope and method of model calculations

Four key characteristics of basinal groundwater flow have been calculated by numerical modelling. The calculations were performed for hypothetical repositories located at depths of 500 m and 1000 m respectively in both recharge- and discharge-areas of topographically defined basins which are underlain by a geologic framework of varying permeability distributions. The four flow characteristics are: 1) „return time", ts, or the travel time of water from a repository to the land surface; 2) „repository-age of water", tr, or the travel time of water from the land surface to the repository; 3) „return route", ls, i.e. the length of flow line leading from the repository to the land surface in the direction of flow; and 4) „fault route", lf, or the total length of that flow line inside of a highly conductive fault which passes also through a repository. These characteristics were determined with reference to a point 500 m below the land surface and 1 km distant from the lateral boundaries of the basin (*Fig.* 2). The point is considered to represent the upper edge of a repository. The repository extends over a surface area of 2x2 km (size of the reference repository in the Canadian disposal concept) and its centre coincides with the basin's lateral boundaries at both the water divide (recharge side) and valley bottom (discharge side).

The general purpose of the modelling experiments was to establish a conceptual reference framework of the key characteristics of regional groundwater flow for the Canadian Shield. To this end, basinal patterns of hydraulic heads, flow lines and travel times were computed for a variety of basin-permeability configurations using geologic data and field conditions typical of Shield conditions.

The geometry of the modelled basin is constant for all variants. It simulates one flank of a centrally symmetrical depression as, for instance, one side of a river valley (TÓTH 1963). The width of the modelled basin's flank is 20 km and its depth at the valley is 4 km. The flow domain is enclosed by impermeable boundaries on the two sides and the bottom, and by a sinusoidal water table, (i.e. a sinusoidal distribution of the fluid potential) along the top (*Fig.* 2). The water table is higher by 400 m at the divide than at the valley bottom.

Two basic, or reference, distributions of basin permeability are used, namely: one homogeneous (*Fig.* 2) and one stratified into three horizontal depth ranges of different permeabilities. The latter case was further modified by the introduction of highly permeable fault zones which lead with a slope from points of fixed depths at the lateral basin boundaries to outcrops at the land surface or horizontally, to the opposite lateral boundary thus abutting against it without outcropping. The purpose of introducing the faults was to examine the potential effects on travel times and flow-path lengths of highly permeable conduits located at or near a repository that might remain undetected, and thus ignored, while modelling real life situations. In the different model variants, the attitude of the faults was changed by discrete steps between a vertical position at the boundary and the horizontal. The various characteristics and conditions of the model are summarized in *Table I.*

The key flow properties were determined by visual interpolation from the model's direct outputs, which are: basinal patterns of equipotentials (hydraulic heads), flow lines, travel times (indicated by time-step beads on flow lines) and isochrone lines of the travel time. Specifically, travel times were estimated by interpolation between computed isochrone values, and travel distances were expressed as relative lengths along flow lines passing through the reference point. The calculations were performed by the code FLOWNET, developed by van ELBURG et al., (ENGLEN & JONES 1986). FLOWNET models two-dimensional

Table I – I. tábla

Model version (Name)	Basin Type	FAULT			TRAVEL TIME OF WATER	
		Position in Basin (same as repository)	Depth at near Boundary (m)	Distance of Outcrop from Boundary (m)	'Return time' from Repository to Surface t_s (years)	'Age of water' àt Repository (years) t_r
HRe0	homogeneous	rep.: recharge fault: none	N. A.	N. A.	$3,4 \times 10^6$	$8,0 \times 10^4$
HDi0	—"—	rep.: discharge fault: none	N. A.	N. A.	$9,5 \times 10^4$	$3,4 \times 10^6$
SRe0	stratified	rep.: recharge fault: none	N. A.	N. A.	8×10^6	$1,25 \times 10^5$
SDi0	—"—	rep.: discharge fault: none	N. A.	N. A.	$1,1 \times 10^5$	$8,0 \times 10^6$
SRe5/1,6	stratified	recharge	500	1600	3×10^6	$2,0 \times 10^5$
SRe5/13,6	—"—	—"—	500	13600	$1,3 \times 10^6$	$3,2 \times 10^4$
SRe5/20,0	—"—	—"—	500	20000	$8,3 \times 10^5$	$3,0 \times 10^4$
SRe5/h	—"—	—"—	500	horizontal	$(3,5 \text{ to } 8,7) \times 10^5$	$3,0 \times 10^4$
SRe10/2,6	stratified	recharge	1000	2600	$2,96 \times 10^6$	$6,5 \times 10^4$
SRe10/11,4	—"—	—"—	1000	11400	$1,17 \times 10^6$	$2,8 \times 10^4$
SRe10/20,0	—"—	—"—	1000	20000	$9,5 \times 10^5$	$2,7 \times 10^4$
SRe10/h	—"—	—"—	1000	horizontal	$(1,83 \text{ to } 5,0) \times 10^5$	$2,7 \times 10^4$
SDi5/2,8	stratified	discharge	500	2800	$1,8 \times 10^5$	$2,6 \times 10^6$
SDi5/11,2	—"—	—"—	500	11200	$2,7 \times 10^4$	$1,26 \times 10^6$
SDi5/20,0	—"—	—"—	500	20000	$2,3 \times 10^4$	$8,5 \times 10^5$
SDi5/h	—"—	—"—	500	horizontal	$2,7 \times 10^4$	$6,5 \times 10^5$
SDi10/2,6	stratified	discharge	1000	2600	$6,3 \times 10^4$	$3,0 \times 10^6$
SDi10/11,4	—"—	—"—	1000	11400	$2,8 \times 10^4$	$1,15 \times 10^6$
SDi10/20,0	—"—	—"—	1000	20000	$2,5 \times 10^4$	$7,0 \times 10^5$
SDi10/h	—"—	—"—	1000	horizontal	$2,5 \times 10^4$	$4,2 \times 10^5$

steady state, groundwater flow in a rectangular, heterogeneous and anisotropic domain of the subsurface with arbitrary water-table configuration, by the technique of finite differences.

Discussion of modelling results

Thirteen hydrogeologic characteristics that have been calculated by the groundwater flow-modelling and are relevant to the development of a strategy for repository site-selection are summarized in *Table II.* In order to emphasize the contrast between conditions in recharge and discharge areas the characteristics for these hydraulic regions are juxtaposed in the Table. The unfaulted stratified basin is considered as the basic, or reference, basin. The hydrogeologic conditions established for this basin variant are accepted as the fundamental rationale for the Recharge Area Concept. The faulted-basin variants have been generated in order to examine if the presence of conduit faults might negate the conclusions drawn from the basic model.

The most fundamental advantage of a repository location in a regional groundwater recharge area as opposed to that in a discharge area is summed up in the first four items in *Table II.* Collectively they indicate that in a recharge area, groundwater flows downward with respect to the land surface, at decreasing velocities which may approach zero in the direction of flow and beneath the water divide. Conditions are opposite, on the other hand, in discharge areas: water moves from depth toward the land surface with increasing intensity in the directions of flow and the thalweg boundary. In the field, the sense of flow

Table II – II. tábla

Item Number	HYDROGEOLOGIC CHARACTERISTICS	GROUNDWATER REGION	
		RECHARGE AREA	DISCHARGE AREA
1 *	hydraulic head gradient	upward	downward
2 *	vertical pressure gradient	less than hydrostatic	greater than hydrostatic
3 *	vertical component of flow	downward	upward
4 *	driving-force past the repository in direction of flow and toward divide	downward weak, decreasing to zero	upward strong and increasing
5 **	minimum return route from repository to surface (unfaulted stratified basin)	greater than 20 km	500 m
6	effect of faults on minimum return route (unfaulted)	reduce to ~20 km	nil
7 **	return-time from repository to surface (unfaulted stratified basin) t_s	8×10^6 a t_{sR}	$1{,}1 \times 10^5$ a t_{sD}
8	effect of dipping faults on minimum return time from repository	reduce to: $(3$ to $0{,}83) \times 10^6$ a	possibly increase up to $1{,}8 \times 10^5$ a, mostly reduce to $0{,}23 \times 10^5$ a
9	effect of horizontal fault on minimum return time from repository	reduce to: $(1{,}83$ to $5{,}0) \times 10^5$ a	reduce to: $2{,}5 \times 10^4$ a
10 **	minimum flow-path length from surface to repository (unfaulted stratified basin)	500 m	greater than 20 km
11	effect of faults on minimum flow-path length to repository (unfaulted)	nil	reduce to ~20 km
12 **	age of water at repository (unfaulted stratified basin) t_r	$\sim 1{,}3 \times 10^5$ a t_{rR}	$\sim 8{,}0 \times 10^6$ a t_{rD}
13	effect of faults on age of water at repository	reduce to: $\sim(2{,}7$ to $3{,}2) \times 10^4$ a	reduce to: $\sim(0{,}42$ to $2{,}6) \times 10^6$ a

* general conditions
** conditions in reference (unfaulted and stratified) basin

directions can be readily determined by measurements of fluid pressures and/or water levels in wells.

As a consequence of the opposite nature of conditions in these hydraulic environments, two associated key characteristics, namely the return-route length and the return time also are more favourable for recharge area locations (*Table II*, Items 5, 7). Contaminants, possibly escaping from a recharge-area repository would have to travel virtually the full width of the basin plus twice the depth to which regional flow would take them. If originating from areas within one kilometre of the divide boundary, this flow penetrates into the low permeability basement thereby delaying contaminant return both by adding distance and reducing velocity; the route length is significantly greater than 20 km. From a discharge area position, on the other hand, the contaminants would only have to travel 500 m, mostly through the high permeability weathered zone, to reach the land surface. The different conditions are amply reflected by the difference in return times (*Table II*, Item 7): 8x106 a for the recharge area repository and 1.1x105 a for the discharge area repository. Both the return-route length and the return time have significant bearings on the safety of a nuclear waste facility. The longer the route, the greater a proportion of the contaminants is adsorbed on the rock matrix's minerals; the longer the travel time the larger proportion of the radioactivity decays.

The age of the water in the recharge and discharge areas (*Table II*, Item 12) are noteworthy from two stand-points. During the 1.3x105 years that descending meteoric waters take to reach a repository in a recharge area they will be largely depleted in free or dissolved oxygen and will not be an oxidizing agent. In the discharge area, on the other hand, by virtue of its high age, an 8x106 year old water could be mistaken to indicate stagnancy, yet it is only 1.1x105 years away from the surface.

All the above numbers are modified by the presence of faults. Nevertheless, all the parameters have minimum values that can be evaluated for realistic conditions.

Thus, faults can reduce the return-route length to a minimum of approximately 20 km for a recharge-area repository, but cannot change the 500 m in a discharge area. Similarly, the return travel times can be significantly reduced by faults in recharge areas: from 8x106 to 0.18x106 years in the absolute extreme (the minimum value of the error bar), but more likely only to approximately 0.8x106 years (*Table II*, Items 7, 8, 9). An important point here to note is that, with the exception of those recharge area faults which run the full length of the basin and outcrop in the valley bottom, none of the faults can convey water directly from the vicinity of the recharge divide to the land surface. But even in these extreme cases, water that descends from the surface within one kilometre of the basin's crest is forced to move across these faults down into the low velocity or the stagnant zone of the basin and then travel its full width, largely through the low permeability basement, to emerge in the discharge area some 107 years later! All these numbers can be increased purposefully further by selecting a basin configuration with a lower elevation difference between valley and the upland, a longer flank and a broader divide than those in the present model. Faults may reduce the return travel times in discharge areas also. In the calculated cases (*Table II*, Items 7, 8, 9) the reduction is from 1.1x105 to 2.3x104 years. (Actually, the upper limit obtained for a near vertical fault is ~ 4x105 years.) However, because return times and return-route lengths are controlled by local conditions in discharge positions, modifying the regional basin characteristics, namely by the choice of the basin, will have little or no effect on these parameters.

Summary and conclusion

1) A new approach in demonstrating the safety performance of an underground nuclear waste disposal facility is proposed. Based on the Recharge Area Concept, it embodies the view that a clear understanding of regional groundwater flow patterns can be exploited so as to have groundwater delay the transport of escaped contaminants to the surface through either entrapment in stagnant zones of no-flow or through transport along a very long flow trajectory. This passive 'safe-fail' system can be seen as adding another „barrier" to the planned system of engineered/geologic multi-barriers as envisioned in the existing general disposal concept adopted internationally.

2) In addition to the enhancement of total system safety, a siting strategy based on the RAC makes it possible to confirm modelling results with field measurements that can be extrapolated far into the future.

3) From the viewpoint of contamination transport by groundwater, recharge areas are superior to discharge areas for the siting of high level nuclear waste

repositories. Recharge area locations assure considerably greater minimum travel-path lengths and return-flow times than do discharge area locations, and their effectiveness can be evaluated and purposefully modified; this type of control is not possible for discharge area locations.

4) The possible presence of, even undetected, faults does not negate nor compromise the theoretical superiority or the suitability of recharge areas.

5) The hydrogeologic conditions required for the suitability of a recharge area location can be recognized and confirmed from field observations, and to the extent needed for safety, evaluated and critically assessed by modelling. This is not possible for discharge-area positions: the sensitivity of regional hydrogeological conditions to changes in their controlling factors is low as compared with that of the local conditions. Consequently, regional model estimates are robust relative to those from local models.

6) Regional groundwater flow can be exploited to enhance the role (utility) of the geosphere as a barrier to radioactive waste transport by judiciously selecting the basin and locating the repository near the basin's crest. Such deliberate exploitation, as it were engineering, of natural conditions is not possible for discharge-area repository-positions.

7) Adoption of the RAC as a siting strategy would greatly minimize the economic cost and simplify the logistics of site screening and selection, especially if properly used with GIS and remote sensing technologies that are presently available and undergoing significant development.

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