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Conceptual model of an underground radioactive waste repository in rock-salt and clay formations in Poland

Key words

Radioactive waste, model of repository, salt dome, clay formation

Abstract

The principal safety requirement for an underground radioactive waste repository (RWR) is its tightness which must ensure that radioisotopes will not be released to the biosphere. The paper presents two conceptual models of the RWR: in salt dome and in clay series which are the only rock formations in Poland suitable for localization of the RWR. Selected aspects of safety problems were presented including the geological and geotechnical barriers. It was found that under conditions encountered in salt domes in Poland the construction of repository of a relevant capacity must include the waste storage in "zubers", which requires further laboratory and field studies.

Introduction

An ultimate storage of radioactive wastes under the conditions of long-lasting, full isolation from the biosphere belongs to the important, interdisciplinary scientific and technical problems.

Due to the serious environmental hazard caused by radioactive wastes the practice has been commonly accepted according to which a country which produced such wastes is obliged to deposit them within its own territory. However, neither the routine methods nor the relevant international legislation have been developed up to date except some directives and recommendations from the International Atomic Energy Agency (IAEA) in Vienna which facilitate the designing of radioactive wastes repositories.

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The rock formations in which the radioactive waste repository (RWR) can be constructed ought to reveal the following features:

— extension sufficient to secure the relevant capacity of workings at designed depth and under the mining-engineering safety criteria,

— sufficient sealing which ensures the elimination of flooding of repository during a particular time span dependent on the type of stored wastes,

— relevant lithology which ensures minimization of unfavourable geochemical and hydrogeological changes caused by thermal effect,

— physico-chemical and geochemical properties which limit the migration of radioisotopes,

— localization in areas free of seismic activity,

— localization which does not disturb the current land-development plans.

The technological solutions include:

— establishing of natural barriers and determination of the time of their safety operation,

— selection of relevant protections during operation of a repository,

— establishing and control of sub-critical conditions during and after the operation of a repository,

— selection of materials and methods of sealing and backfilling,

— closure of repository which would eliminate the release of radionuclides.

The detailed requirements for particular repository depend on the category of stored wastes.

General categorization of radioactive wastes dependent of their self-activity included high-, intermediate and low-active wastes.

In 1994 the IAEA proposed a new categorization system which considered not only self--activity but also the concentration of long-lived-radiation emitters. Hence, the following categories were distinguished:

— high-level wastes (HLW) and spent nuclear fuel (SNF),

— intermediate/low-level, long-lived wastes (I/LLW-LL),

— intermediate/low-level, short-lived wastes (I/LLW-SL),

— very low-level wastes — out of evidence (EW).

It is recommended that the first two categories should be deposited in deep geological formations due to required long-term isolation from the biosphere.

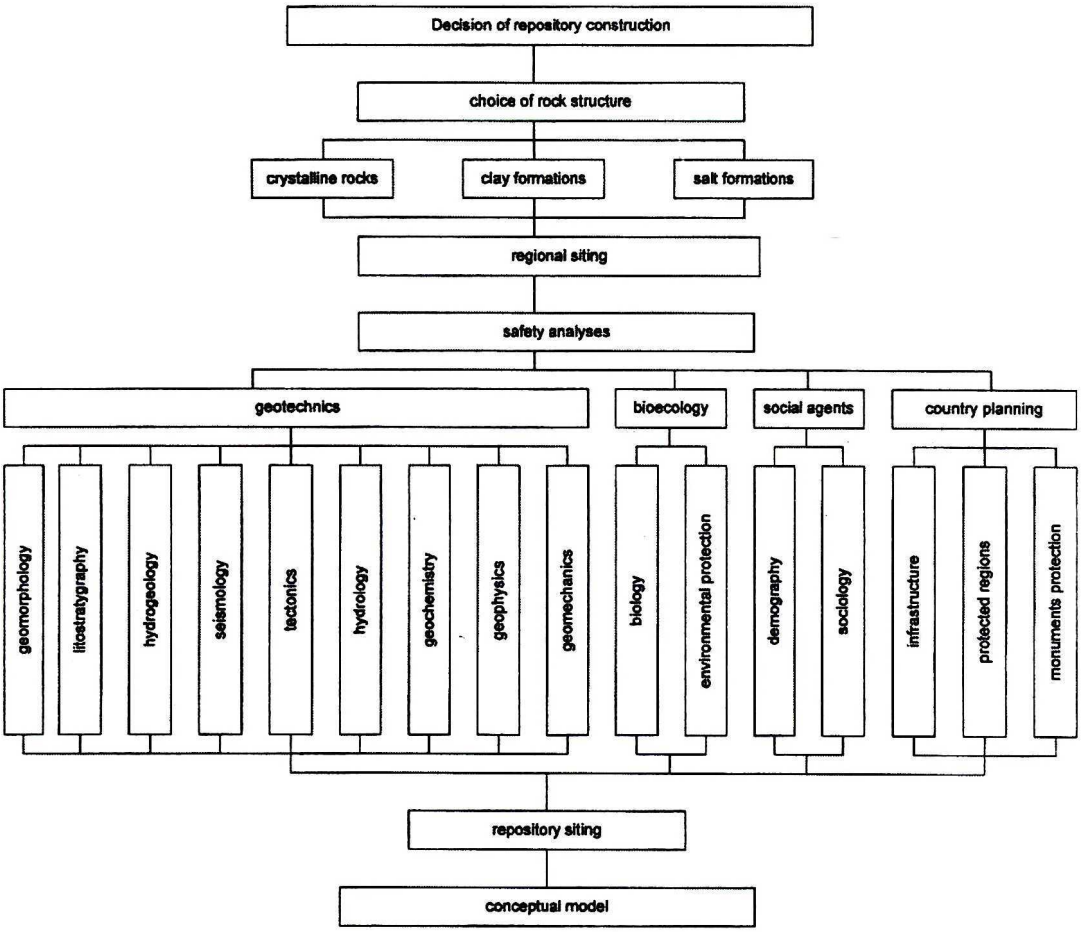
1. Localization of repository

The problem of evaluation and selection of underground repository consistent with the world-wide experience is shown in Scheme 1.

1.1. Selection of geological structure

Preliminary analysis of existing domestic materials considering the size of structures, their geology and hydrogeology allowed to select the following rock formations which may fit to the generally accepted criteria for underground, deep-seated RWR:

— igneous and metamorphic complexes,



Scheme 1. Problems of site selection for underground repository of radioactive waste

Schemat 1. Problematyka wyboru lokalizacji podziemnego składowiska odpadów promieniotwórczych

— clay formations,

— rock-salt deposits.

Basing upon the existing knowledge, the initial selection criteria of rock formations were: depth and size of structures.

Furthermore, the conformance of geological and mining-engineering conditions with the criteria for the RWR were analysed in detail for selected structures.

In the next step the characterizations of selected structures were compared (state of recognition, regional geology, hydrogeology and seismics, detailed geological conditions including lithostratigraphy, petrography, chemical and mineralogical compositions, tectonics and petrophysical properties).

The analysis revealed that geological and hydrogeological conditions of magmatic complexes in north-eastern Poland are unfavourable for the construction of RWR because

igneous and metamorphic complexes are dissected by numerous tectonic structures and, thus, separated into blocks of insignificant areas.

The Quaternary and Mesozoic formations which cover the crystalline basement host numerous water horizons. It must be considered that waters circulating in magmatic complexes are in hydraulic contact with horizons in sedimentary cover. This fact eliminates the structures as suitable for the construction of RWR.

The analysis of domestic structures led to the selection of 4 structures which meet the criteria for construction of the HLW and SNF repositories (Ślizowski i in. 1998):

— 3 salt domes in Central Poland,

— Upper Keuper clay series (so-called "Upper Gypsum Series") in the Fore-sudetic monocline.

The selected structures — salt domes and clay series — differ substantially in geological arrangement which plays decisive role in recognition of a spatial model of repository.

The salt domes are not the rock-salt monoliths but are usually composed of alternating salt and barren layers.

The generalized stratigraphic column of Zechstein sequence in Kujawy area is bipartite and includes the lower unit (Od) composed of Oldest and Older Halites (Z1 and Z2, respectively) whereas the upper unit (Og) comprises mostly clay layers ("zubers") with Younger and Youngest Halites (Z3 and Z4, respectively).

Differences in petrophysical properties of lower and upper units are reflected in the internal structure of a salt dome. The rock-salt series are strongly folded and tectonically deformed. The most typical features are (Ślizowski i in. 1983):

— very high fold amplitudes which results in very high-angle dips of layers down to the designed depth of the RWR,

— older Halite layers which form the cores of anticlines protrude upwards through the enclosing, younger, barren strata which, in turn, constitute the cores of synclines.

The selected clay series occurs in central part of the Fore-sudetic Monocline, in southern Wielkopolska. The geological structure has been recognized basing upon the results of deep drillings localized close to the borders of selected area. The drillings revealed favourable conditions for construction of the RWR. The "Upper Gypsum Series" selected for the design shows thickness up to 240 meters and is capped by 300-meters-thick Rhaetic claystones.

The Upper Gypsum Series is a monotonous complex of mottled clays interbedded with mudstones. The layers are almost flat-lying but the top surface of the series is diversified due to variable thickness and relief of the underlying "Reed Sandstone" layer.

1.2. Analysis of safety conditions

In accordance with the world standards, the application for concession for design and construction of the HLW and SNF repository must include the analysis of safety conditions, as shown in Fig. 1, followed by the safety assessment report submitted to the state authorities. The report should contain proofs for the very low probability of radionuclides leakage from the repository and their migration to the biosphere.

The safety assessment report comprises, among other elements, the computer simulation of so-called "maximum design failure". The report should present proofs that even the destruction

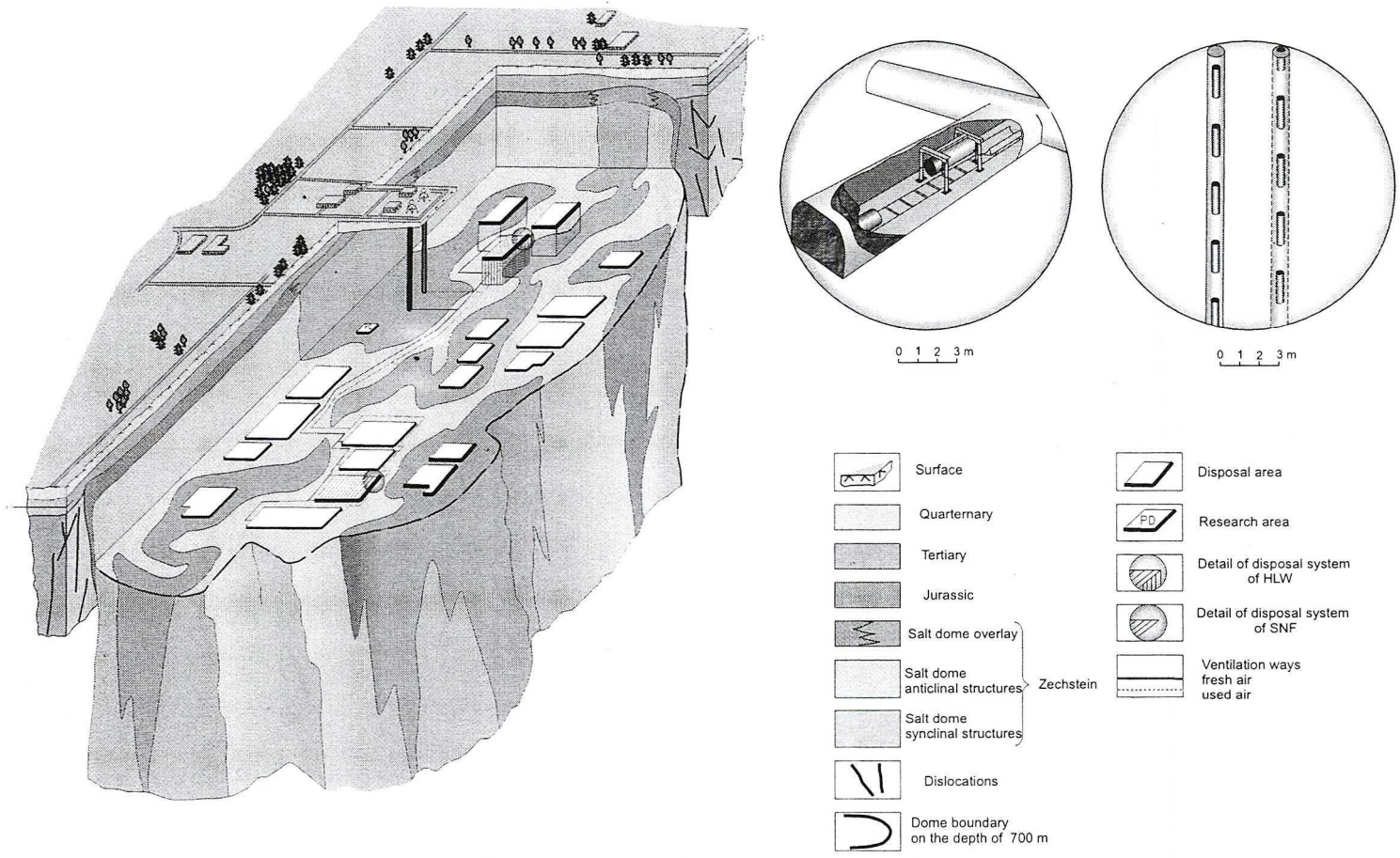


Fig. 1 Conceptual model of radioactive waste repository in salt dome

Rys. 1. Model koncepcyjny składowiska odpadów promieniotwórczych w wysadzie solnym

of repository due to natural processes will not rise the concentrations of radioisotopes in surrounding biosphere above the permissible level.

The concept of multi-barrier containment is commonly accepted according to which several natural and engineering barriers are set up between the wastes and the biosphere. Even if one is breached, others still prevent the migration of radionuclides. Such barriers are e.g.: form of occurrence (e.g., vitrification), sealing method (e.g., corrosion-resistant containers), backfilling material, hosting rock formation, caprocks, etc.

The risk evaluation is based upon mathematical modeling for which input functions and parameters of rock formations are of vital importance. Hence, the aquisition of reliable data set requires not only laboratory analyses and measurements but also the field observations.

2. Models of repositories in salt domes and clay formations

The conceptual models of repositories for the HLW and SNF are presented in Figs. 1 and 2 (Ślizowski i in. 1999a). Complicated, interdisciplinary character of the problem causes that even brief presentation of all the factors considered during modeling and shown in Scheme 2 would far exceed the acceptable volume of the following publication. Therefore, only the selected factors, typical for particular model will be shortly discussed.

The basic element of any model is the storage area (Fig. 1, 2), which includes a system of galleries. Wastes are located in storage galleries in the following mode:

— the SNF containers, 5 meters long and 1 meter in diameter, are distributed in rows, at 5 meters spacing (Fig. 1 and 2),

— the HLW containers, 135 centimeters long and 42 centimeters in diameter, are located in boreholes of diameters 60—80 centimeters drilled down from the bottoms of storage galleries. In salt domes vertical boreholes of depth down to 200 meters are proposed (Fig. 1) whereas in clay formations two parallel rows of inclined wells down to 50 meters deep are designed (Fig. 2).

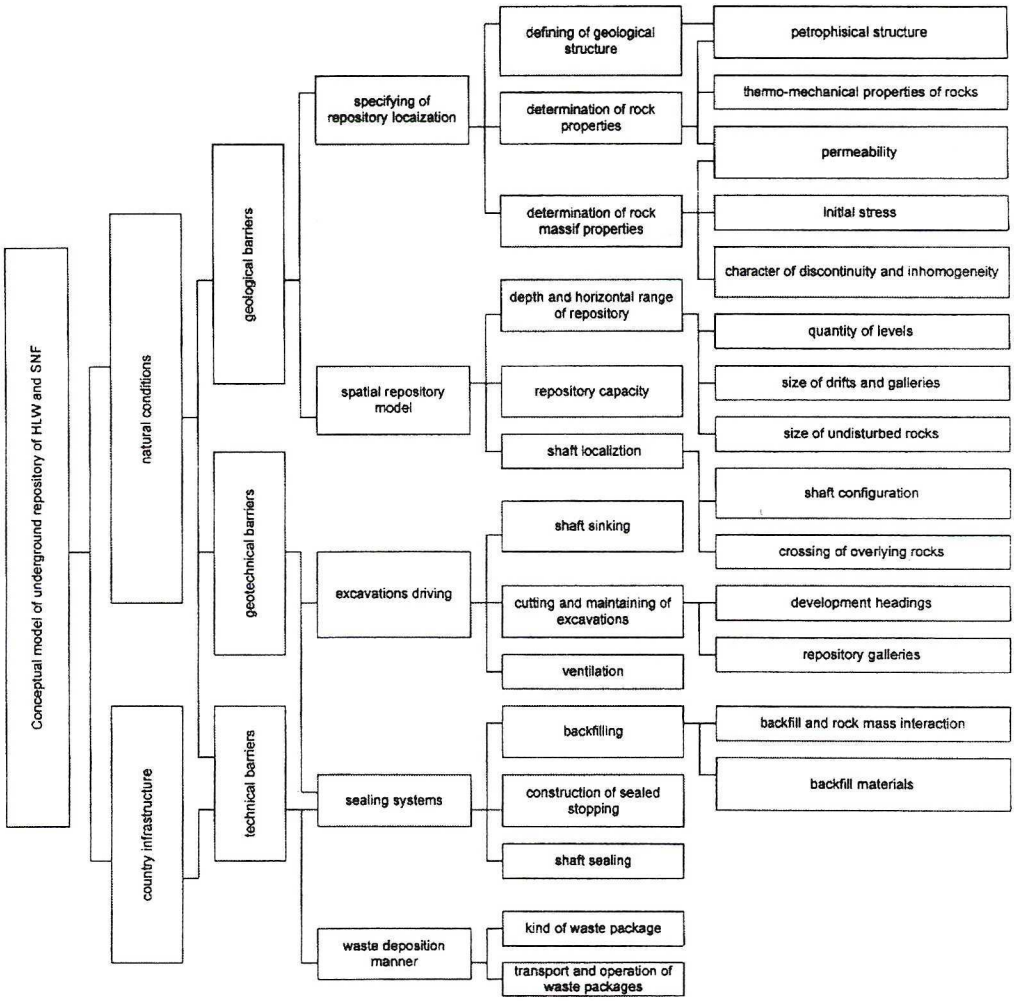
The dimensions of galleries should enable the remote positioning of containers, the backfilling and the efficient ventilation. The spacing between storage galleries determines the capacity of storage field, i.e. the capacity of the repository.

2.1. Petrophysical properties

According to the selection criteria, the storage fields should be located in a homogeneous rock formations.

In salt domes the localization of storage fields was proposed in the two lithologically different formations: rocks-salts and "zubers" (clay-abundant rock-salt) due to high variability of lithology and complicated internal structure of a salt dome.

Such a design implies difficulties in development of particular fields as cutting through the transitional layers between Oldest and Older Halites will be necessary. Such transitional zones may provide solutions of variable chemistry, which may, in turn, force the changes in advancing direction of developing works.



Scheme 2. Problems taken into consideration for conceptual model of underground RWR

Schemat 2. Zagadnienia rozważane przy opracowaniu modelu koncepcyjnego podziemnego składowiska odpadów promieniotwórczych

Therefore, the main tasks of exploration and developing works within the salt dome are:

— recognition of the boundaries of anticlines and synclines,

— recognition of the boundaries of rocks-salt complexes within the anticlines,

— recognition of the boundaries of homogeneous "zuber" complexes within the synclines.

Localization of storage fields in the clay strata of the Upper Gypsum Series, if its thickness is favourable, can be more regular and may not require the large-scale exploration works. However, the presence of water-bearing "Reed Sandstone" may cause water hazard if discontinuities reach the galleries. Thus, exploration works will be necessary in order to determine the practical extent of storage field.

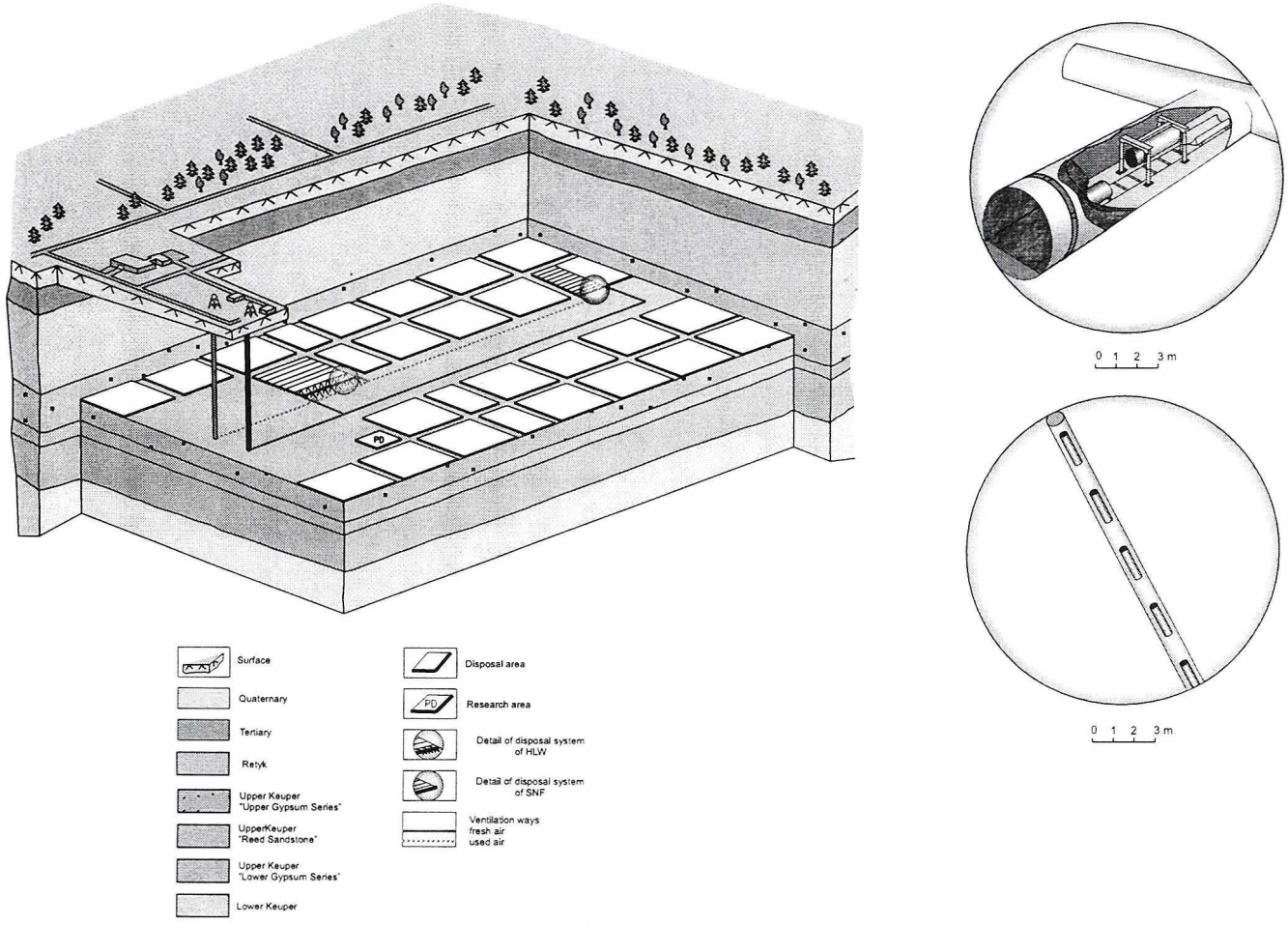


Fig. 2. Conceptual model of radioactive waste repository in clay formation

Rys. 2. Model koncepcyjny składowiska odpadów promieniotwórczych w formacji iłów

Depth of repository is determined by geological and hydrogeological conditions of the structure as well as by the required isolation time of wastes from the biosphere.

For a salt dome repository the designed thickness of protection zone under the salt table is 400 meters. Hence, the shallowest level of repository in the selected salt domes can be developed at depth 700—900 meters below surface.

For the clay formation repository the geological conditions enable the development of storage field at depth about 550 meters below surface. The Rhaetic clay formation caprock provides the sealing from overlying groundwater horizons. The bottom protection zone of significant thickness, which separates the repository from the "Reed Sandstone", determines the vertical extent of this particular localization.

The consideration presented above allow to conclude that the principal factors controlling the spatial model of the RWR are: internal geological structure and general dip of rock formations.

In salt domes the horizontal extension of repository is limited due to termination of the structure and complicated internal pattern but vertical expansion is possible.

In layered clay formations the horizontal extension is limited only by tectonic discontinuities but single-level character is determined by thickness.

2.2. Thermomechanical properties and permeability

The principal problem which controls the functioning of a repository is the tightness. From thermomechanical point of view the main factors are: thermal expansion and rheologic properties, particularly the creep rate (i.e. the increment of strain in time at constant stress). High intensity of creeping lowers the long-lasting strength but, from the other hand, creeping causes the self--tightening of microfractures, which enhances the sealing properties of rocks. The creep of salt and clay strata is very diversified and creep rates may differ several hundreds of times at given stress and temperature. More compact is the clay rock — less favourable are its rheological properties.

Important problem is also the recognition of gas and brine inclusions in halite and in "zubers". The release of natural moisture at rising temperature combined with permeability of rocks may be the source of potential hazard not only because rheological properties of rocks may significantly change but also, as proved by studies in the USA (Baar 1977), the liquid inclusions tend to migrate towards the source of heat which, consequently, may facilitate the corrosion of containers.

2.3. Initial stress and the character of discontinuity and inhomogeneity

The optimum conditions for waste storage would be provided by large structures consisting of tectonically undisturbed, homogeneous rocks which remain under the conditions of lithostatic initial stress of equal vertical and horizontal components. However, in the area of Poland such structures practically do not exist, both in clay complexes and in selected salt domes (Poborska-Młynarska, Ślizowski 1999). The determination of initial stress is a very complicated problem, particularly for rock-salt which reveals high rheological properties and for which the standard measurement methods used for elastic rocks are inapplicable. The practical experience

demonstrates (Mateja 1995) that measurements of the changes of stress (e.g. caused by working of galleries or by temperature rise) are easier than the determinations of absolute values and directions of principal stresses.

2.4. Number of levels and dimensions of workings and protection zones

In the presented conceptual models the single-level repositories were considered, particularly in clay formations where thickness is a limiting factor. In salt dome structures the two-or multi-level repositories can be taken into account, depending on the volume of the SNF.

Determination of dimensions of galleries and protection zones is a complicated problem which requires the development of a correct mathematical and physical models of geological structure. The safety conditions of repository can be challenged only by rising temperature. Considering only the gravity load exerted on a working, the storage galleries and chambers might have been even larger than required and more closely spaced. The conditions of repositories are more favourable than those of standard mines because the designed storage system includes almost immediate backfilling of the workings.

Different problems are faced in the case of developing and communication workings which must be available during the full life-time of a repository. Temperature rise and consequent, abrupt creep acceleration may result in loosening of rocks in walls and roofs, and in decrease of working volumes of galleries. Such process can be eliminated by determination of proper distances between main workings and heat sources. At present, it is difficult to determine precisely the spacing of workings but distances between 50 and 100 meters seem to be realistic. Another important problem related to temperature rise is, at the present state of knowledge, a critical thermal capacity of the whole repository which cannot be exceeded. Excessive increase in temperature of rock formation may cause serious changes in hydrogeological environment around the repository. Therefore, the very thorough considerations must be made and for the Waste Isolation Pilot Plant designed in the USA the 40 meters spacing between the storage workings was proposed in order to control effectively the heat flow.

2.5. Shaft pattern and overburden sinking

The optimum solution for the RWR would be the sinking of 3 shafts:

— crew and supply, intake shaft,
— ventilation shaft (outtake),
— waste-operation shaft.

In the proposed models the double-shaft solution was considered which meets the safety requirements for the designed frequency of container transport. The ventilation shaft will also play the role of waste-operating one.

In the double-shaft solution the individual shafts can be localized in the peripheries of the storage field or as twin system, centrally or peripherally in relation to storage fields.

Analysis of the factor decisive in shaft localization led to the proposal of twin system with shafts sunk in the periphery of storage fields. In the case of salt dome such positioning was forced

by geological structure and necessary access to the younger cyclothems. In the case of clay formation the twin system is most efficient and ensures: (i) perfect ventilation of workings, (ii) change in advancing directions of galleries and (iii) closure of repository from margins towards the shafts which limits the influence of temperature on the main communication galleries.

The shafts which are practically the only connections between the repository and the surface cause the risk of fluid migration into the workings. The shaft construction must ensure its proper functioning during the life-time of repository. However, after the closure and backfilling the shafts are potential migration routes of solutions into the repository and contaminated liquids out of it, into the biosphere.

Therefore, shafts must be localized and sunk in a proper mode which ensures their stability and full protection against water hazard. This, in turn, requires the perfect recognition of geological and hydrogeological conditions, selection of proper sinking techniques and casing method as well as relevant measurements enabling the prediction of casing behaviour.

Shaft sinking in salt domes is a difficult operation due to hydrogeological condition of overlying formations. Thus, crucial for shaft localization is the sufficient knowledge of geological structure and hydrogeological conditions of the overburden, the clay-gypsum cap and roof part of the salt dome, immediately beneath the salt table.

The overburden comprises Cainozoic formations which host several water horizons of variable parameters. The clay-gypsum cap is an inhomogeneous product of salt dome weathering. Its lithology is controlled by the composition of salt formations from which it origins. The lower petrophysical unit of Zechstein formation (Od) dominated by the Oldest and Older Halites is covered by gypsum cap. The cap contains abundant brine, which may be in direct contact with the salt table and may cause its leaching. The upper unit (Og) dominated by "zubers" is covered by clay cap which is low in water and provides sealing of the salt table from the overlying water horizons.

These differences in properties result in much deeper position of salt table over the lower unit and in the presence of brine-filled caverns and fissures which enable migration of groundwater into the roof part of the salt dome. On the contrary, the salt table forms local elevations over the upper unit. Considering both the Polish and the European experience in salt mining, it is proposed that the shafts should be localized in the clay cap of low water potential, i.e. over the Younger Halite (Z3, brownish "zubers") and Youngest Halite (Z4, red "zubers"). This allows the opening of rock-salt at shallower depth. The position of future shaft must be confirmed by the borehole drilled along its designed axis.

In the clay formation of the Fore-sudetic Monocline the principal factor determining the deposition of heat-generating radioactive wastes — increasing temperature of rocks — forces localization of shafts in the peripherial parts of the storage field. The protection pillars left behind will shield the shafts against high temperature during life-time and closure of repository (if the operation from margins towards the shaft is designed).

The completed gravimetric and geoelectric surveying confirmed the variable thickness of overburden and the presence of water horizons in Quaternary and Tertiary strata. Analysis of geoelectric data allowed the recognition of the properties of formations down to the top of Rhaetic sequence. Changes in resistivity of Tertiary strata enabled the selection of most favourable localization in southeastern part of the study area (Ślizowski i in. 1999b).

2.6. Influence of backfill on waste deposition

Interaction between the salt formation and the backfill results in much lower compression of filled workings in comparison with empty ones due to the resistance from the fill. Squeezing causes the compaction of filling material and, hence, the appearance of stress. In an unheated working the convergence rate of working and the increment rate of stress within the fill should decrease as the difference between stresses in rocks and in fill decreases. In a heated working the stress in fill increases almost linearly, as demonstrated by German studies (Schneefus, Droste, Heusermann, Sonke 1994). Such feature can be explained in terms of an increasing thermal conduction of fill which results in faster heating of rocks and thus, in higher convergence rate. It is concluded that changes in thermal conduction of a fill compensate its resistance caused by compaction.

Precise recognition of this process will be important for verification of thermomechanical, numeric model of repository which is necessary for design.

Conclusions

The worldwide experience points out that storage of radioactive wastes (particularly the HLW/LL ones) must be preceded by long-term studies which must include theoretical approach as well as laboratory experiments and "on site" observations and measurements. Localization of each repository must be considered and analyzed individually. Such studies have been undertaken in early 1960-ties, in countries which produced nuclear energy. The still more rigorous environmental standards suggest that in the nearest future not only the radioactive wastes but also other kinds of hazardous wastes may be subjected to the similar procedures. If the principle is accepted that a country which produces wastes must deposit them in its own territory the studies on applicability of rock formations to the storage of hazardous wastes should be continued despite the strategic decisions concerning the development of nuclear energy production. The up-to-date results indicate that general safety requirements for the HLW storage in Poland are met by the three salt domes in Central Poland and by the clay formation in the Fore-sudetic monocline.

In the selected salt domes the single, large repositories cannot be constructed because of the lack of sufficiently large space within the anticlinal structures. Instead, the storage fields are proposed to be constructed separately in rock-salts and in "zubers".

In the nearest future the experimental evaluation of salt domes as hazardous waste repositories can be carried on in the Kłodawa rock-salt mine.

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MODEL KONCEPCYJNY GŁĘBINOWEGO SKŁADOWISKA ODPADÓW PROMIENIOTWÓRCZYCH W SKAŁACH SOLNYCH I ILASTYCH W POLSCE

Słowa kluczowe

Odpady promieniotwórcze, model składowiska, wysad solny, formacja iłów

Streszczenie

Podstawowym warunkiem bezpieczeństwa jaki musi spełniać podziemne składowisko odpadów promieniotwórczych (SOP) jest jego szczelność, gwarantująca nieprzedostanie się radionuklidów do biosfery. W pracy zaprezentowane zostały dwa modele koncepcyjne SOP w wysadzie solnym i pokładzie skał ilastych, jako jedynych strukturach skalnych, w których istnieją możliwości zlokalizowania składowiska na ziemiach polskich. Przedstawione zostały wybrane aspekty zapewnienia bezpieczeństwa z zakresu barier geologicznych i geotechnicznych. Stwierdzono, że w warunkach polskich wysadów solnych dla uzyskania odpowiedniej pojemności składowiska należy rozpoznać możliwości składowania odpadów w solach zubrowych, co wymagać będzie dalszych badań laboratoryjnych i in-situ.