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MONITORING AND MANAGEMENT OF GEOENGINEERING REPOSITORIES OF RADIOACTIVE WASTE

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Abstract

The paper provides the approach to the management of the repositories of radioactive waste, which include monitoring of contaminants migration into environment in case of natural or technogenic accidents which may influence on soil, subsoil waters and repository' installations structures. The aim of the research is the development of system of estimation of radioactive state of the environment in the area of radioactive repository, based on the cumulative data, the knowledge base, set of rules of production, logical deduction gear and conclusion building gear by means of uncertain and incomplete input data. It is proposed the use of several models for the spectral characteristics of radioactive pollutants migration. The evaluation of possible damages of repository containment is made. The heuristics for the radioactive waste repository expert system are developed. The proposed procedure of quality definition of decision making for the radioactive waste repositories management should take into account the reliability of information about the state of the radioactive repository.

Keywords: **Radioactive waste; Repository; Expert system; Spectral characteristics; Fuzzy set; Heuristics.**

1. INTRODUCTION

Environmental safety ensuring is the actual problem as for the radioactive waste repositories at the nuclear power plants so and for tailings and mine dams at mining enterprises [7]. Moreover, monitoring of radioactive pollutants migration is the essential part of such wastes storages management and should include understanding the role of diffusion, filtration and real conditions of environment in the affected of repositories of radioactive waste areas [8].

The going systems of monitoring for the radioactive waste repositories include the simulation with the only model of pollutants migration [1] and do not take into account the possibility of natural or man-made impacts on the facilities stability [2, 6].

As any monitoring system that deals with fuzzy data and uncertainty conditions, radioactive geoengineering repositories operate with the limited retrievals of data and the laws of their distributing are unknown a priori. So here, the methods with the use of the Bayes theorem, fuzzy set theory and linguistic estimations of researched data are used widely [4, 5, 3].

2. THE EXPERT SYSTEM FOR THE RADIOACTIVE REPOSITORIES MONITORING AND MANAGEMENT

2.1. Real repository status definition

The aim of the research is the development of the system of estimation of radioactive state of the environment in the area of radioactive repository.

The expert system of repositories monitoring and management includes the rules of production or heuristics (*IF* (precondition), *THEN* (action) [index of distinctness – ID]), the quintets conjunctions and action which includes the quintet's parameters value definition. For the action's quintet ID computation there are used the rule's ID together with the ID of related to the rule quintets. ID statements define ID precondition. If the quintet is not formed the ID are calculated as:

$$ID = OI + RI(1 - OI), \quad RI, OI > 0$$
$$ID = -(|RI|(1 - |OI|)), \quad RI, OI < 0 \qquad (1)$$
$$ID = \frac{|OI| + |RI|}{1 - \min\{|OI|, |RI|\}}, \; RI, OI < 0.$$

Let's consider several heuristics for the radioactive wastes (RAW) at mining or nuclear power enterprises:

IF ([the RAW spot dynamics is within the 2σ limits (SPOTSTAB)] *AND* [natural and/or man-made accidents during the previous measurements' cycles are absent (NMMA=0)]), *THEN* [monitoring procedure is routine (MONROUT)].

IF [SPOTSTAB] *AND* [NMMA=1], *THEN* [together with MONROUT the causal monitoring MONCAUS for the points which are laid on the direction from accident epicenter (AEC) should be provided, i.e. MONROUT + MONCAUS AEC].

IF [SPOTSTAB] *AND* [it is a tendency to increase of average monotonous displacement of RAW spot in the same direction within 2σ limits (TMD2σ), *THEN* [MONROUT + MONCAUS MD] (MONCAUS MD – extra causal monitoring in monotonous RAW spot displacement's direction).

IF [SPOTSTAB] *AND* [NMMA=0] *AND* [NONSTABSPOTNOCR], *THEN* [check the RAW expansion model conformity CHECKEXPMODCONF] (NONSTABSPOTNOCR – RAW spot dynamics is not critical).

Checking the model may be realized by definition of its sensitivity to parameters' deviations and adjustment of certain parameters for the purpose of accordance the predicted on the time of extrapolation and real measured at that time values of RAW. After this adjustment the RAW spot dynamics modeling is implemented along the all period of functioning of repository. There is also another permissible step (if there are several models of RAW spot dynamics): implementation of concurrent modeling by several models and using the model that has the minimal metrics of predicted distribution of RAW spot relative to the real distribution.

IF ([$SPOTNSTAB_{n-1}$] *AND* [$SPOTNSTAB_n$] *AND* [NMMA=0] *AND* [NONSTABSPOTNOCR] *AND* [the vectors of RAW spot shifts are situated in different quadrants – VECTSPOTSHIFTDIFQUAD]), *THEN* [CHECKEXPMODCONF]. The [$SPOTNSTAB_{n-1}$] and [$SPOTNSTAB_n$] correspond to the RAW spot dynamics detection in (n-1)-th and n-th measurement cycles.

IF ([SPOTNSTABn-1] *AND* [SPOTNSTABn] *AND* [NONSTABSPOTNOCR] *AND* [NMMA=0] *AND* [the vectors of RAW spot shifts are situated in the same quadrant – VECTSPOTSHIFTSAMQUAD]), *THEN* [CHECKEXPMODCONF] *AND* [check the density of separate blocks or containment as a whole – CHECKCONTDENS].

IF ([NONSTABSPOTCRIT] *AND* [NMMA=1] *AND* [VECTSPOTSHIFTDIFQUAD], *THEN* ([it is necessary to change MONROUT at the critical procedures of monitoring MONCRITIC] AND [use the RAW expansion critical models RAWEXPCRITMOD]. MONCRITIC assumes the changing of range – instead of 0.5 *Bk/l* the threshold of several *Bk/l*, changing of parameters' measuring frequency in the all points around repository with the selective measurements in the points in which the parameters have the largest values. RAWEXPCRITMOD – the models concerned with formation of the channels along which the RAW expansion is realized more strongly (for example along the subterranean waters-bed or along the joint fissure and so on).

IF ([NONSTABSPOTCRIT] *AND* [NMMA=1] *AND* [VECTSPOTSHIFTSAMQUAD], *THEN* [MONCRITIC] AND [RAWEXPCRITMOD] *AND* [man-made protective barrier establishing across the RAW spot movement path PROTBAR if the movement is directed to the settlements, the water supply points and so on].

One of the main problem of repository's impermeability is the seismic resistance which is realized by adequate repository's design and by means of installations and design monitoring (with the help of direct and mediate methods) for the exposure and elimination the danger of their destruction, the great landslides data collection, knowledge level increasing about deviations in the main direction of subterranean waters redistribution, drawing up the seismic dangerous maps connected with the repository's influence zone. Mentioned monitoring in routine process periodically analyzes the repository conditions but in the cases of natural or man-made accidents which may influent on the repository conditions the code of causal monitoring is activated.

For simplifying of the mentioned types of monitoring procedures there are recommended the accelerometers setting in separate assemblies of repository's structure for the recording of vibrations caused by possible landslide sources. Similar action promotes the analysis and interpretation of appeared situation. Seismic landslides and landslips, which challenge the soil vibration, generate the destructive waves in the reservoirs and rivers, dangerous for the installations and soil structure. On the maps characterized the prospective surface movements (for example, natural frequency and intensity of earthquakes) repositories in-situ it is necessary to insert the instructions related to possible damages, local geological structure, probability of steady landslides, landslips and soil rarefactions inside of every seismic zone and immediately in zone of repository location.

Analysis and interpretation of information about hypothetic results of each landslide or earthquake are very difficult because of lack the precise and single meaning data. Therefore these facts should be taken into account in process of acceptance of decision. After the significant earthquake the installations may be damaged but as a rule the results of these injuries are difficultly observed – there may be microcracks, changes in internal repository's bearing structures and so on. The results may be observed later, for example by increasing of RAW components concentration in subsoil waters in wells drilling around of repository. Index of RAW components leakage may be represented as "summary area of microcracks – to summary area of repository walls and bottom" relation (or "summary area of microcracks – to area of repository bottom" relation). As a repository damage scale it may be used the following categories of status:

A – damages are absent or immaterial;

B – the slight or medium damages;

C – the significant damages;

D – entire damage of repository when its functioning is not possible.

The monolithic constructions as repositories theoretically may be checked by their reaction on the external vibrations. Their natural frequency and external source vibration's absorption factor may be used for evaluation. As it is known, the more damages – the less (droningly) natural frequency but external source vibration's absorption factor from the beginning arises and then – decreases. Hence, the alternations in constructions' inflexibility and especially vibrations may be used as indexes of structural damages. Such research should be carry out after each earthquake that is fixed in-situ of repository. It is necessary also to fulfill some analytical inspection, which supposes the careful study of initial constructive calculations, designed specifications, and implementation of extra structural analysis combined with field observations and test data.

The first step in containment's evaluation procedure consists of status scale definition (for example – four):

"0" – the absence of whatever problem (during the several previous years there were no natural or man-made accidents which may influence on soil, subsoil waters and repository' installations structures; the monitoring results witness that level of RAW components pollution in the points being periodically controlled is not characterized by monotonous changes and registered deviations out of natural background in limits of doubled error of measuring methods or measuring instruments.

"1" – presence of negligible problems (during the previous routine monitoring cycle it was a certain accident epicenter of which was remote from repository but in controlled zone some small shocks were observed; during the previous and current routine monitoring cycles the monotonous changes of RAW components pollution distribution were not revealed but the marginal coming out of 2σ limits in one or several controlled points were observed).

"2" – presence of increased filtration of RAW components (during the previous and current routine monitoring cycles and causal parameter measurement in points which are positioned along over direction to the meaningful accident epicenter – although this epicenter is substantial remote from the repository's influence zone – the monotonous movement of RAW components spot is found out and it oversteps the limits 2σ in every direction).

"3" – presence of essentially damaging of repository (during the previous and especially current routine monitoring cycles and causal parameter measurements the important parameter changes ($\gg 2\sigma$) are found out first of all in the points joined along the considerable accident's epicenter direction and this epicenter is relatively close to repository).

The repository containment status scale definition may be presented as in the Table 1. The containment status scale evaluation has some uncertainty and that fact may have influence upon the decision-making procedure. If the repository containment status is represented in digital form as a belonging function μ_d then for the above-mentioned stated cases the next table may be arranged (Table 2). Here [0] – absolute non true, [0.1–0.3] – the poor level of truth,

Table 1.
The repositories status evaluation

Class	Filtration RAW (max)	Repository conditions evaluation	Overall technical conditions
0	< 2σ	Good	Damages are absent. The all processes are flow under license
1	≤ 2σ	Satisfactory	Damages are absent or immaterial
2	> 2σ	Non satisfactory	Approximately uniform expansion of RAW spot evidence of overall marginal damage of compaction which may be compensated by drainage
3	≫ 2σ	Breakdown	Monotonous growth of RAW spot along the direction on the accident's epicenter evidence of essential damage of repository. It is necessary to build the artificial barrier between repository and important zones near the repository, which are on the way of RAW spot movement. If the RAW spot movement stopping is impossible it should be considered the question of these zones evacuation or alternation of their activity

[0.4–0.5] – essential level of truth, [0.6–0.7] – the high level of verity, [0.8–0.9] – almost the verity, [1.0] – well-defined truth.

The belonging to status, which corresponds to classes "0", "1", "2" or "3", is derived from the equation

$$\mu = max\ \{\mu_0, \mu_1, \mu_2, \mu_3\}. \tag{2}$$

The real repository status may be defined out by taking into account the accumulated effect of seismic stresses (landslides, fractures, shocks) influence. For that, it is necessary to:

- Determine the frequency and strength of shocks in-situ of repository over the all observations period and on the base of these data formulate the forecast in advance.
- Simulate the influence of accumulated landslides, fractures and shocks on the repository's constructions from point of view the probability of structure changes in repository walls and bottom that may stipulate the formation of microcracks net, summary area of which promote the RAW components departure (migration).
- Determine the threshold (THR) exceeding of which guarantees the more than 50% probability of microcracks net rise.

After listed steps, it is necessary to equip the stations for repository status monitoring by accelerometers connected with automated monitoring system. The accelerometers data should be accumulated in the next format: [date, shocks amount, integrated value of shocks strain, the maximal acceleration in succession, series duration].

It is necessary to bring in heuristics the data listed in the format and at the same time transmit them to the base, where possible – with the comments (if it is connected with subsequent RAW spot dynamics detection, which is correlate with the fact).

Table 2.
The repository containment status in digital form

Class	Membership function	d = 0	d = 1	d = 2	d = 3
"0"	μ_d	0.9	0.8	0.4	0.1
"1"		0.8	0.9	0.6	0.2
"2"		0.2	0.9	0.9	0.8
"3"		0	0.5	0.8	0.9

At the same time the heuristics, presented above, may be formulated as following:

1-a. *IF* ([SPOTSTAB] *AND* [NMMA=0] *AND* [TLS=0]), *THEN* [MONROUT] (here TLS=0 means that tectonic landslides [TLS] are absent or ATLS ≤ THR1 where ATLS – the accumulated TLS, THR1 – threshold for the case when the maximal shock value is within limits of average minimal shock during the all-time of observations).

2-a. *IF* ([SPOTSTAB] *AND* [NMMA=1] *AND* [TLS=1], *THEN* ([MONROUT + MONCAUS AEC]) (here TLS=1 means that tectonic landslides occur but their values are small, although they exceed the TRH1).

3-a. *IF* ([SPOTSTAB] *AND* [TMD2*σ*] *AND* [TLS=2]), *THEN* ([MONROUT] *AND* [MONCAUS MD]) (here TLS=2 means that tectonic landslides are noticeable and accumulated landslides ALS are within limits THR1 < ALS < 0.2 THR).

4-a. *IF* ([SPOTSTAB] *AND* [NMMA=0] *AND* [NONSTABSPOTNOCR] *AND* [TLS=2]), *THEN* [CHECKEXPMODCONF].

5-a. *IF* ([SPOTNSTABn-1] *AND* [SPOTNSTABn] *AND* [NMMA=0] *AND* [NONSTABSPOTNOCR] *AND* [VECTSPOTSHIFTDIFQUAD] *AND* [TLS=2]), *THEN* [CHECKEXPMODCONF].

6-a. *IF* ([SPOTNSTABn-1] *AND* [SPOTNSTABn] *AND* [NMMA=0] *AND* [NONSTABSPOTNOCR] *AND* [VECTSPOTSHIFTSAMQUAD] *AND* [TLS=3]), *THEN* [CHECKCONTDENS]. (Here TLS=3 means that tectonic landslides are noticeable and accumulated landslides ALS are within limits 0.2 THR < ALS ≤ 0.4 THR).

7-a. *IF* ([NONSTABSPOTCRIT] *AND* [NMMA=1] *AND* [TLS=3] *AND* [VECTSPOTSHIFTDIFQUAD], *THEN* [MONCRITIC].

8-a. *IF* ([NONSTABSPOTCRIT] *AND* [NMMA=1] *AND* [TLS=4] *AND* [VECTSPOTSHIFTSAMQUAD], *THEN* ([MONCRITIC] *AND* [RAWEXPCRITMOD] *AND* [PROTBAR]. (Here TLS=4 – tectonic landslides within ALS limits 0.4 THR ≤ ALS ≤ 0.7 THR).

2.2. Decision making procedure for the radioactive waste repositories management

The functional scheme of the repositories monitoring system consists of subsystem of environmental information collection and subsystem of information and analytical analysis. This system is proposed to be integrated to united state system of environmental monitoring, which will monitor the air, water, soil, geological changes, waste etc. and control the risks of emergencies. The highest level of this system is a territorial information and analytical center, which must perform the following functions: obtaining information from information-analytical centers of the middle level and from the part of automated (stationary and mobile) environmental control systems; continuous analysis of environmental information, trends and ecologically hazardous areas and zones; modelling and forecasting the development of emergencies and their consequences; making recommendations for the adoption of operational decision-making in emergencies; formation of a bank of statistical data on the ecological status of individual cities and districts and the entire region in whole; simulation and long-term forecasting the environmental state of ecosystems. Moreover, information and analytical centers solve the problems of identifying the risks of emergency environmental situations and forecast their development in a particular area, taking into account the specifics of radioactive repositories, local industrial and agricultural production, geographical, climatic and meteorological features.

The principles and stages of constructing expert systems for decision making for environmental monitoring and management of radioactive repositories include the stages of conceptualization, concretization, formalization and implementation of tests. As the main criteria for checking the developed expert system, the quality of decisions is selected, which is evaluated by checking the quality and correctness of judgments while solving real problems, establishing the acceptability of the character of dialogue with the user, defining functional technical and software tools, etc.

At the same time, each situation, regardless of whether it relates to the assessment of the degree of pollution of the environment or management of technical objects in a difficult situation under conditions of indistinct and incomplete information or decision-making, is characterized by the presence of risks that need to be taken into account.

When establishing the apparatus and means of control and analysis of reliability of information about the state of the radioactive repository, it is very important to justify the choice of specific control methods that take into account the specifics of the object of control, the conditions under which the system operates and the requirements for the object and system.

If there are known:

– coefficient of output uncertainty K_{ouc};

– coefficient of control of the process

$$K_C = \{\sum_{i=1}^{l} \lambda_i D_i\} / \{\sum_{i=1}^{l} D_i\}, \quad (3)$$

where λ_i – efficiency coefficient of the i-th control method, which is defined as the ratio of the number of detected errors A to the total number of errors (both detected and those that are not detected) $A + B = \delta$, and D_i – i-th operation of information control;

– total amount of information Q;

– number of system errors, that are not detected, B;

– estimated total coefficient of uncertainty

$$K_{uc} = [\sum_{i=1}^{l} \frac{\delta_i}{Q}(1-\lambda_i)D_i] / (\sum_{i=1}^{l} D_i), \quad (4)$$

or

$$K_{uc} = [\sum_{i=1}^{l} B / Q) D_i] / (\sum_{i=1}^{k} D_i), \quad (5)$$

it is possible to determine the coefficient of rationality of the control system

$$K_{r.c.} = K_{оис}(1 - K_{л}) / K_{ис}, \quad (6)$$

which for values $K_{rc} < 1$, that is, $K_{оис}(1 - K_c) < K_{ис}$ indicates that the control system is built irrationally or the technology of data processing in the system is not rational.

Equally important is the choice of conceptual, informational and behavioral models of the control system and verification of their reliability by using "reverse" operations. This verification may include the following steps (procedures):

- consideration of the design of the model and the feasibility of its development;
- establishing connection of the idea and the feasibility of developing a model with determined, randomized and average values of the characteristics of the model;
- research of accepted approximations of real processes;
- consideration of criteria of the effectiveness of parameters and variables;
- research of accepted propositions and hypotheses;
- detecting the connection of the results of the two previous stages with real processes;
- analysis of the system of disturbing factors and characteristics of the operator;
- research of the interconnections of all these factors;
- verification of the information and its sources used for model development;
- consideration of the whole control procedure in connection with the definition of the task of the system;
- consideration of the task.

When selecting controlled parameters, their informational value should be considered (separately for the case of operational control of normal modes and separately for emergency control). For operational control, the informational value of a parameter can be determined as:

$$Z_{on} = (\sigma_x / C_x) \ln(\sigma_x / \lambda_x)\rho, \quad (7)$$

and for emergency – according to the following:

$$Z_a = \frac{C_x}{x_a - m_x} \ln \frac{\sigma_x}{\lambda_x} \rho \quad (\text{for } \xi \geq x_a), \quad (8)$$

where σ_x – average square deviation of the parameter ξ; C_x – the maximum rate of change of the parameter ξ in transitional modes; λ_x – an error of the measuring device; ρ – coefficient that takes into account the distribution of probabilities of values $x \in \xi$; x_a – the minimum value of the parameter ξ, which corresponds to the emergency situation; m_x – mathematical expectation ξ.

In this case, the generalized characteristic of the informational value of the parameter can be represented as:

$$Z_n = Z_{on} \cdot Z_a. \quad (9)$$

In addition, the value of information can be expressed through increasing the probability of achieving the goal:

$$I = \log (p_1/p_0), \quad (10)$$

where p_0 – probability of achieving the goal before receiving information, and p_1 – the same after receiving the information. If after receiving additional information the probability of achieving the goal is reduced, this indicates the need to move to an alternative strategy. And in this sense, additional received information has a real value, since it saves resources and time by refusing from nonperspective strategy.

As for the choice of a particular set of control methods, it is necessary to consider a number of factors that determine not only the possibilities of certain technical means, requirements to the control system, the conditions under which the processes of collection, transmission, processing and storage of information take place, but also economic indicators.

3. CONCLUSIONS

The developed expert system for the radioactive repositories monitoring and management includes the cumulative data, the knowledge base, and set of rules of production, logical deduction gear and conclusion building gear by means of uncertain and incomplete input data.

To avoid the errors in radioactive components migration forecast it is necessary to use several alternative models with the same input data. Such simulation allows getting the spectral characteristic in points of checking at the predetermined time of forecast.

The proposed procedure of quality definition of decision making for the radioactive waste repositories management provides a reconsideration of the task from a slightly different point of view, which contributes to a deeper and more comprehensive assessment of the system and allows creating an optimal conceptual model that is, adequate to a mathematical model and, as a result, creates conditions for effective control of reliability.

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