Journal of Engineering Physics and Thermophysics, Vol. 75, No. 5, 2002

ANALYSIS OF THE SAFETY OF THE BURIAL GROUNDS OF DECONTAMINATION WASTE OF CHERNOBYL ORIGIN IN THE TERRITORY OF BELARUS

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UDC 504.064.36:621.039.76

Unsatisfactory conditions of storage of decontamination waste (DW) in the storages formed in the territory of Belarus after the Chernobyl accident require the evaluation of the level of protection of the environment and population. The potential hazard of the decontamination waste burial grounds (DWBGs) has been evaluated based on the use of a generalized multichamber model that was verified by comparing the calculation results and the results obtained by the American (GW SCREEN) model. The characteristics of the 24 largest and most hazardous DWBGs are given and the evaluations of their safety are presented. The zones of influence of these storages, whose size varies from 100 to 330 m, have been determined. The reliability of the prediction evaluation of a possible hazardous radioactive contamination of water near the storages has been verified using the Dudichi DWBG as an example.

Decontamination waste burial grounds formed in the territory of Belarus after the Chernobyl accident are found, as a rule, near populated areas. As a result of the hastily taken decontamination measures, they turned out to be placed in territories where there was no necessary and sufficient isolation of decontamination waste preventing radioactive contamination of the environment [1–4].

An analysis of the storage conditions of decontamination waste has shown that of the 92 DWBGs investigated and registered

1) only 11 have a waterproof base;
2) in 27 storages the waste can be flooded, and in 13 storages the waste can be underflooded by ground water in the case of seasonal change in its level;
3) the waste in three storages can be washed out by surface water;
4) 62 storages are preserved at present, i.e., the waste in them is covered by a local soil layer of thickness 0.5–1.0 m, on which grass is sown;
5) three storages are at the stage of putting them into a prolonged storage;
6) 23 storages are acting (additional burial of waste can be made);
7) four storages require that a decision on reburial be made.

Thus, many of the DWBGs placed in the territory of Belarus bring the threat of a possible secondary contamination of the environment. In this connection, it became necessary to evaluate the degree of their potential radioenvironmental hazard for the purpose of revealing the level of protection of the environment and the population living near the storages.

The DWBGs studied belong to radioactive-waste storages of the near-surface type. In the system of protective barriers of these storages, important elements are man-made or natural waterproof shields. The role of a natural protective barrier is played by the aeration zone insulating the water-bearing horizon from direct contact with the decontamination-waste storage. Such disposition of radioactive waste in the geosphere determines the conceptual model of migration of radionuclides from a decontamination-waste storage to a site of water management and the block diagram

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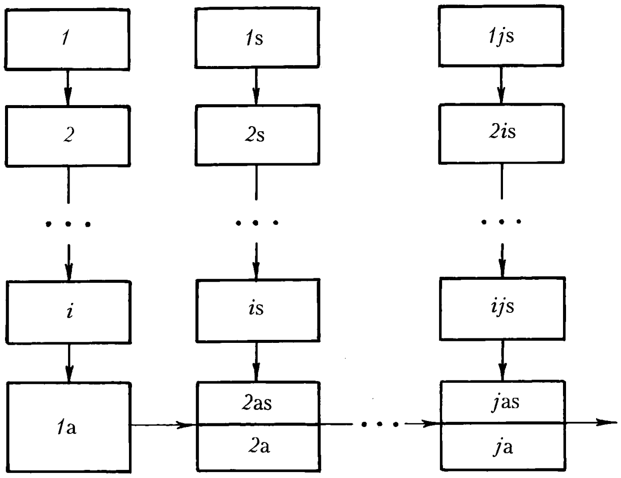

Fig. 1. Block diagram of the model: 1) volume of the DWBG; 2–*i*) volumes of the engineering and natural barriers (vertical migration); 1a) volume of mixing of the contaminated flow arriving with infiltrated moisture from the DWBG with ground water; 2a–*j*a) volumes of transfer of radionuclides by ground water beyond the territory of the storage; 1s–1*j*s) volumes of the upper contaminated soil layer of the territory adjacent to the DWBG; 2s–*i*s) volumes of the grounds constituting the aeration zone; 2as–*j*as) volumes of the water-bearing horizon contaminated with radionuclides that migrate from the territory adjacent to the DWBG.

of the calculation model (Fig. 1). Since DWBGs are placed in contaminated territories, the block diagram of the model also accounts for the ingress of radioactive contaminants into the ground water as a result of the migration of radionuclides from the surface layer of the soil of the territories adjacent to the DWBGs.

To describe the processes of migration of radionuclides from a decontamination-waste storage to a site of water management, we used a generalized multichamber model with lumped parameters [5], which includes an arbitrary number of vertical and horizontal control volumes, the chamber of junction between which is a mixing volume (Fig. 1).

The model is based on the following assumptions:

a) the porous medium in the separated control volumes in which the migration of radionuclides occurs is homogeneous and isotropic;

b) radionuclides are washed out from the waste by atmospheric precipitation or ground water under hydraulically stationary conditions and conditions of continuous operation of the objects;

c) radioactive contaminants are transferred in dissolved form;

d) interaction of radioactive impurity in the water–decontamination waste and water–soil systems is equilibrium and it is described by the linear Henry law;

e) dilution of the contaminants in the water-bearing horizon occurs in a layer of finite thickness;

f) the velocity of motion of the infiltrated moisture is determined from the balance between the atmospheric precipitation, its evaporation, and the infiltration feed of the ground water;

g) the velocity of motion of the ground water is determined by the Darcy law with the use of the data of hydrogeological investigations.

With these assumptions, the processes in the chambers are described by the system of ordinary differential equations of mass transfer with averaged parameters which account for the washout and convective transfer of radionuclides by the infiltrated moisture and ground water, the interaction of the radioactive impurity with the soils, and radioactive decay [5].

The model allows one to calculate the total specific activities (C_t) and the specific activities of the radionuclides in dissolved form (C_w) in the containing grounds and in the water-bearing horizon during the period of the po-

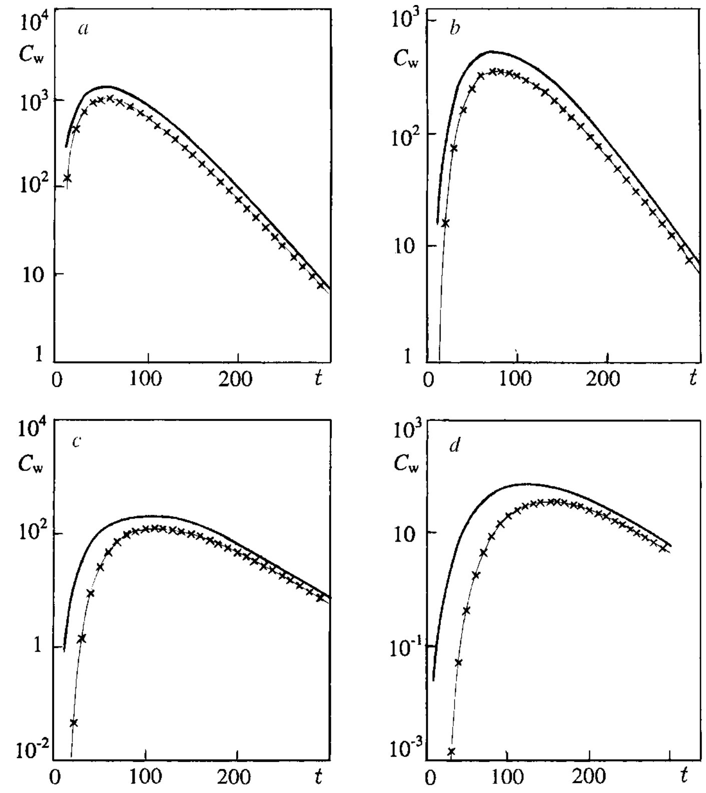

Fig. 2. Comparison of the specific activities of ^{90}Sr in water-soluble form, calculated by the chamber model (solid curve) and by the American GW SCREEN model (points) as functions of the time (t) and the distance (L) from the boundary of the storage: a) L = 25, b) 70, c) 120, and d) 180.

tential hazard of decontamination waste as well as the individual effective rate of dosage from the consumption of potable water, which are additional indicators and criteria of radioenvironmental safety of the storages.

The model proposed was verified based on the comparison of the results of calculations by the given model and by the American GW SCREEN model [6]. The GW SCREEN model is a semianalytical model, the main assumption in which is the advection-dispersion mechanism of transfer of a contaminant in the water-bearing horizon.

Figure 2 compares the calculations by the multichamber model (Institute of Radioenvironmental Problems of the National Academy of Sciences of Belarus) and by the advection-dispersion (GW SCREEN) model. The following features have been revealed:

1. It has been established that the profiles of the calculated specific activities of radionuclides in the ground water at different reference space-time points are in good qualitative agreement.

2. The calculations by the chamber model give higher values of the content of the contaminant in the water-bearing horizon than the calculations by the advection-dispersion model. This is justified by the physical essence of the chamber model based on the assumption that the contaminant is completely mixed in the control volume, i.e., it is infinitely dispersed within the limits of the chamber [7].

3. The disagreement between the results is no more than 30% and can be decreased by selecting the hydrodispersion coefficients whose experimental and theoretical determination is very difficult and is characterized by a substantial uncertainty.

Evaluation of the potential hazard of a DWBG was carried out based on the multichamber model proposed. At present, the safety of the 16 largest DWBGs placed in the resettlement zone of in the Pripyat fallout area and the 8 most hazardous (underflooded) DWBGs placed in the Sozh area of fallout of Chernobyl origin in the Gomel’ Region has been evaluated (Table 1).

Evaluation of the safety of DWBGs is associated with prediction of the environmental state within the zone of influence of storages during the period of potential hazard of decontamination waste on the basis of the safety in-

TABLE 1. Characteristics of the Analyzed DWBGs of the Pripyat and Sozh Areas of Fallouts (Gomel' Region)

Name of DWBG	Conditions of disposition	Occupied area 10^3, m^2	Volume of DW 10^3, m^2	Thickness of barriers, m	Specific activity of DW, kBq/kg		Margin of activity in the storage, GBq	
					^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr
Pripyat' fallout area								
Babchin-3, Khoiniki District	Foundation pit of depth 5 m	8.5*/3.4	12.2	4.7/6.3***	4.1/10.8**	0.7/1.8**	63.1	10.1
Babchin-1, Khoiniki District	Ditches of depth 1.6 m	19.2/5.6	9.6	0/0.8	2.7/6.2	0.3/0.6	33.2	3.5
Babchin-2, Khoiniki District	Open pit of depth 1–3 m	7.7/2.3	3.7	1.5/2.0	2.6/18.2	0.3/0.9	13.0	1.5
Tul'govichi, Khoiniki District	Foundation pit of depth 4.5 m	14/9.7	11.3	0/1.5	3.2/12.5	0.3/0.6	44.5	3.6
Kozhushki, Khoiniki District	Foundation pit of depth 1.5 m	7.2/1.2	7.2	0/1.2	2.2/4.4	0.1/0.6	21.1	1.1
Novoselki, Khoiniki District	Foundation pit of depth 3.5 m	14/6.7	6.0	2.0/3.0	1.9/3.7	0.05/0.11	15.0	3.7
Poselichi, Khoiniki District	Ditches of depth 2.5 m	4.3/1.6	2.1	0/0.9	1.8/8.9	0.2/0.8	4.8	0.5
Omel'kovshchina, Khoiniki District	Pits of depth 2.5 m	2.0/0.6	1.0	1.0/2.5	2.9/10.1	0.1/0.5	3.7	0.2
Moriton, Bragin District	Foundation pit of depth 7 m	66.0/13.0	41.0	0.3/4.5	5.3/12.6	1.3/1.9	271.0	67.0
Savichi-1, Bragin District	Foundation pit of depth 5.5–8 m	14.3/5.9	16.8	2.0/7.5	4.4/9.9	0.4/0.7	102.6	10.1
Savichi-2, Bragin District	Open pit of depth 3 m	14.2/5.9	4.6	0/0.3	1.3/3.1	0.2/0.5	7.8	1.2
Pirki, Bragin District	Foundation pit of depth 4.6 m	1.01/5.5	7.3	2.0/2.5	1.4/2.8	0.23/0.44	18.5	3.03
Pet'kovshchina, Bragin District	Foundation pit of depth 6 m	7.9/2.2	5.3	4.0	2.3/6.7	0.3/0.5	15.5	1.85
Mikulichi, Bragin District	Open pit of depth 3 m	10.6/4.6	4.1	0.4/1.0	0.2/4.1	0.3/0.48	12.0	1.4
Bragin, Bragin District	Open pit of depth 2.3 m	6.7/0.85	1.2	0/0.5	1.7/2.8	0.31/0.52	2.6	0.48
Nudichi, Bragin District	Dump in the forest	90.2/59.8	31.2	1.5/5.0	0.96/1.04	0.09/0.1	1.5	0.14
Sozh fallout area								
Zarech'e, Vetka District	Foundation pit of depth 1–1.5 m	5/2.5	3.7	0/0.4	7.8/10.7	0.3/0.67	37.0	1.1
Svetilovichi-1, Vetka District	Dumps and ditches of depth 1.5–2.5 m	–./2.15	1.7	0/0	11.8/22.6	0.07/0.11	26.0	0.16
Starye Gromyki, Vetka District	Open pit of depth 4.0 m	1.2/0.87	1.1	0/0.7	5.9/13.0	0.27/0.41	8.51	0.41
Proletarskii-1, Vetka District	Open pit of depth 1.5 m	2.9/0.61	1.0	0/0.5	4.8/10.0	0.16/0.3	6.3	0.2
Krasnoe Znamya, Dobrush District	Ditches of depth 1.2 m	0.86/0.71	0.78	0/0.1	2.6/5.6	0.03/0.05	2.6	0.03
Strumen'-1, Korma District	Open pit of depth 2.0 m	6.0/0.11	0.132	0/0	10.7/27.0	0.15/0.255	1.96	0.03
Gorodok-1, Korma District	Open pit of depth 3–4 m	1.5/0.89	2.2	0/0	5.2/10.4	0.074/0.13	1.6	0.02
Dudichi, Chechersk District	Open pit of depth 1.5–3.0 m	1.34/1.3	1.1	0/0	12.0/18.5	0.18/0.31	19.2	0.25

*The total area of the DWBG is given in the numerator; the area occupied by DW is given in the denominator.

**The average and maximum values of the specific activity of DW are given, respectively, in the numerator and the denominator.

***The average and maximum thickness of the engineering barrier are given, respectively, in the numerator and the denominator.

TABLE 2. Results of Calculation of Radionuclide Migration from the DWBGs of the Pripyat Fallout Area (conservative estimates)

Name of DWBG	$T_{\text{p.h}}$, years	$C_{\text{w max}}$ ($L = 0$ m), Bq/m^3		$C_{\text{w max}}$ ($L = 100$ m), Bq/m^3	t, ($L = 100$ m), years	Z, m
		^{90}Sr	^{137}Cs	^{90}Sr	^{90}Sr	^{90}Sr
Babchin 3	370	$2.0\cdot10^3$	~ 0	370	230	~100
Babchin 1	320	$4.0\cdot10^4$	290	$9.3\cdot10^3$	40	~300
Babchin 2	335	$2.1\cdot10^3$	~ 0	224	130	~100
Tul’govichi	320	$2.4\cdot10^4$	$1.3\cdot10^3$	$4.2\cdot10^3$	80	~300
Kozhushki	320	$2.6\cdot10^4$	320	$5.1\cdot10^3$	70	~300
Novoselki	310	$9.7\cdot10^3$	~ 0	~ 0	310	~100
Poselichi	330	$3.2\cdot10^4$	300	$6.0\cdot10^3$	70	~300
Omel’kovshchina	310	$6.6\cdot10^3$	~ 0	6.0	300	~100
Moriton	370	$4.4\cdot10^4$	~ 0	600	170	~150
Savichi 1	340	$6.6\cdot10^3$	~ 0	$2.0\cdot10^3$	~170	~240
Savichi 2	310	$7.5\cdot10^4$	$1.0\cdot10^5$	$1.0\cdot10^4$	50	~330
Pirki	310	$2.0\cdot10^4$	~ 0	1000	60	~200
Pet’kovshchina	320	5700	~ 0	1200	50	~200
Mikulichi	310	$1.4\cdot10^4$	~ 0	96	300	~100
Bragin	310	$3.5\cdot10^3$	$2.0\cdot10^3$	800	10	~150
Nudichi	245	200	~ 0	~ 0	~ 0	~100

TABLE 3. Results of Calculation of Radionuclide Migration from the Underflooded DWBGs of the Sozh Fallout Area (conservative estimates)

Name of DWBG	$T_{\text{p.h}}$, years	$C_{\text{w max}}$ ($L = 0$ m), Bq/m^3		$C_{\text{w max}}$ ($L = 100$ m), Bq/m^3	t ($L = 100$ m), years	Z, m
		^{90}Sr	^{137}Cs	^{90}Sr	^{90}Sr	^{90}Sr
Zarech’e	325	$6.8\cdot10^3$	40.0	87.0	110	≤100
Svetilovichi 1	330	$1.3\cdot10^3$	$4.9\cdot10^3$	182.0	60	≤100
Starye Gromyki	330	$1.6\cdot10^3$	75.0	0.15	120	≤100
Proletarskii 1	320	$3.0\cdot10^3$	37.0	20.0	110	≤100
Krasnoe Znamya	290	478.0	384.0	1.7	110	≤100
Strumen’ 1	360	$4.8\cdot10^3$	$2.7\cdot10^3$	12.0	70	≤100
Gorodok 1	320	$2.4\cdot10^3$	$1.3\cdot10^5$	414.0	60	~170
Dudichi	340	$5.8\cdot10^3$	$6.4\cdot10^3$	900.0	60	~180

dicator — the calculated specific activity of radionuclides in the upper water-bearing horizon. The zone of potential influence of the storage is determined by calculation. It corresponds to the region in which the content of radionuclides arriving at the ground water from the decontamination-waste storage decreases in the process of their migration in the water-bearing horizon to the limiting values in potable water which correspond to the following values of the Republic’s permissible levels (RPL-99): $C_{\text{w RPL}}$ = 10,000 Bq/m^3 by cesium-137 and $C_{\text{w RPL}}$ = 370 Bq/m^3 by strontium-90.

In Table 2, the results of conservative prediction evaluations of the potential hazard of DWBGs in the Pripyat fallout area are presented. Its analysis points to the fact that the existence of a natural barrier (Table 1) decreases significantly the amount of radioactive contaminants arriving at the ground water. In this case, migration of ^{137}Cs in the storages considered is limited by the aeration zone if there is a natural barrier or by the region of mixing of radioactive contaminants with ground water directly under the storage in the case of its underflooding.

Strontium-90 possesses a higher mobility than cesium-137. In this connection, the contamination of the ground water with strontium-90 can reach $(0.02–7.5)\cdot10^4$ Bq/m^3 directly under the storage and $0–1\cdot10^4$ Bq/m^3 at a distance of 100 m from the storage (Table 3).

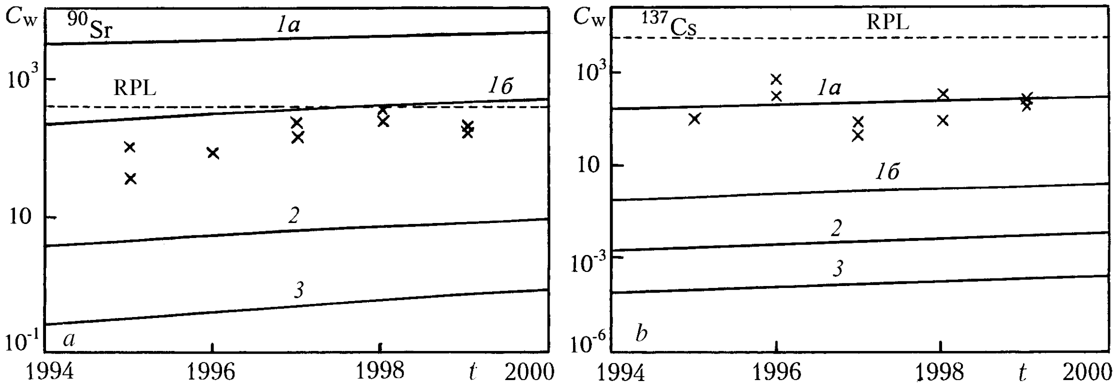

Fig. 3. Comparison of calculation and experimental data on radioactive contamination of ground water near the Dudichi DWBG (control hole, L = 25 m) for different model variants [a) flooding; b) underflooding]: 1) conservative, 2) average, and 3) low estimates of the specific activities of radionuclides in the ground water; points, their experimental values.

For the storages analyzed, the evaluated dimensions of the zone of their influence do not exceed 330 m (Table 2), and the time of potential hazard of the storages ($T_{\text{p.h}}$) covers a period of 245 to 370 years [5].

The results of the prediction evaluations of the potential hazard of the DWBGs in the Sozh fallout area presented briefly in Table 3 have shown that six of the storages considered have an influence zone of no larger than 100 m and two storages have an influence zone of about 180 m.

Evaluation of the influence of the contaminated territories adjacent to the storages on the state of the ground water has led us to the following conclusion: ^{137}Cs is practically completely retarded in the upper soil layer ($h \leq 50$ cm); ^{90}Sr can reach the level of ground water and its contribution to the total contamination of the upper water-bearing horizon within the storage influence zone is 1–20%.

Extensive experimental material has been accumulated as a result of continuous monitoring of radioactive contamination of the soils and ground water in the zone where the DWBGs controlled are placed. It allowed us to verify the reliability of the prediction evaluations made with the use of the data of observations of the state of the natural media near the Dudichi DWBG. The close proximity of the observation holes to this object (25 m) and the yearly study of the ground water allowed us to reveal the dynamics of change of their quality near the storage already in the current decade.

A feature of the Dudichi DWBG is that the decontamination waste in the storage can be flooded by ground water as a result of a seasonal change in its level. Because of this, the model variants of flooded and underflooded storages were considered as the main scenarios. Figure 3 shows the results of the prediction evaluations of the contamination of the ground water near the Dudichi DWBG with allowance for the uncertainty of the initial information [5] and a comparison of them and the experimental data.

The comparison allowed the following conclusions:

1. The results of the analyses of the samples of ground water taken periodically during the years 1995–1999 are within the limiting evaluations of the content of ^{90}Sr and ^{137}Cs in the water-bearing horizon obtained by calculation with allowance for the uncertainty of the initial information.

2. The conservative prediction evaluations (curves 1a and 1b in Fig. 3) are the closest to the observation results. It should be noted that the experimental data are comparable with the conservative evaluations for ^{90}Sr for the calculation scheme of underflooding and for ^{137}Cs for the scenario of flooding of decontamination waste. Such disagreement can be due to both the insufficiently correct selection of the physicochemical characteristics of the waste and the geological medium for calculations and the quality of taking and analyzing the samples of ground water, which involves certain difficulties under field conditions.

3. The calculation results and the monitoring data agree within the limits of the uncertainty of the initial information. The experimental and calculation profiles of the ^{90}Sr and ^{137}Cs concentrations coincide qualitatively. This indicates that the model proposed can be used for prediction evaluations of DWBG safety.

The calculated data on propagation of radioactive contaminants from the DWBGs and the territories adjacent to them to the ground water were also compared to the results of analysis of the samples of soils, grounds, and ground water taken during the years 1994–1999 near the controlled objects Babchin-1, Babchin-3, Kozhushki, Savichi-1, Moriton, and Mikulichi. The comparison has shown that the calculation and experimental data agree within the limits of uncertainty of the initial information [5]. The best agreement is observed between the calculated values of the specific activities of radionuclides and the results of the analysis of the samples of grounds in the unsaturated zone. The calculations and the experimental data on contamination of the ground water agree to a lesser extent. The disagreement obtained can be explained by both the uncertainty of the initial information used in prediction evaluations and the inaccuracy of the measurement and analysis of the samples under laboratory conditions as well as by the insufficient number of measurements made. The latter requires that a more branched system of hydrogeological observation holes be developed at the sites of disposition of DWBGs and radiation monitoring of the state of the ground water near these objects be conducted for many years.

Satisfactory agreement between the results of the calculations performed by the multichamber and advection-dispersion models and their correlation with the experimental data of the field and laboratory investigations point to the correctness of the prediction evaluations of radioactive contamination of the ground water near the decontamination waste burial grounds.

NOTATION

$T_{\text{p.h}}$, time of potential hazard of the storage, years; t and t (L = 100 m), time and time of the maximum radioactive contamination of the ground water at a distance of 100 m from the storage, years; C_{t} and C_{w}, total specific activity of radionuclides in the medium and specific activity of radionuclides in dissolved form, respectively, Bq/m^3; $C_{\text{w.max}}$ (L = 0 m) and $C_{\text{w.max}}$ (L = 100 m), maximum specific activities of radionuclides in the water of the volume of mixing of contaminants with ground water and at a distance of 100 m from the storage, respectively, Bq/m^3; Z, size of the zone of influence of the storage, m; h, thickness of the soil layer; L, distance from the storage, m; i, set of vertical chambers; j, set of horizontal chambers. Subscripts: t, total; w, water; a, water-bearing horizon; p.h, potential hazard; s, soil, ground.

REFERENCES

1. G. Z. Serebryanyi, J. V. Rolevich, A. A. Gvozdev, A. A. Barklai, N. B. Golikova, S. E. Starobinets, and L. A. Polivko, in: *Proc. 5th Int. Conf. on Radioactive Waste Management and Environmental Remediation "ICEM'95,"* Vol. 2, Berlin (1995), pp. 1629–1630.
2. V. V. Skurat, N. M. Shiryaeva, A. A. Gvozdev, G. Z. Serebryanyi, N. K. Myshkina, S. E. Starobinets, and V. V. Kotovich, in: *Proc. 5th Int. Conf. on Radioactive Waste Management and Environmental Remediation "ICEM'95,"* Vol. 2, Berlin (1995), pp. 1417–1419.
3. A. A. Gvozdev, J. V. Rolevich, N. B. Golikova, G. Z. Serebryanyi, S. E. Starobinets, G. G. Sidorenko, and N. M. Shiryaeva, in: *Ext. Abstr. of Papers presented at Int. Conf. "Ten Years after the Chernobyl Disaster (Scientific Aspects of the Problem)"* [in Russian], Minsk (1996), p. 69.
4. A. A. Gvozdev, N. B. Golikova, G. Z. Serebryanyi, S. E. Starobinets, and V. Ya. Timofeeva, *Vestsi Nats. Akad. Navuk Belarusi, Ser. Fiz.-Tékh. Navuk,* No. 2, 156–158 (2000).
5. V. V. Skurat, N. M. Shiryaeva, N. K. Myshkina, A. A. Gvozdev, G. Z. Serebryanyi, and N. B. Golikova, *Evaluation of the Potential Hazard of the Burial Grounds of Decontamination Waste in the Territory of Belarus* [in Russian], Preprint IRÉP-33, Minsk (2001).
6. A. S. Rood, GW SCREEN: *A Semi-Analytical Model for Assessment of the Groundwater Pathway from the Surface of Buried Contamination. Theory and User's Manual*, Version 2.0, Idaho Natl. Lab. (1994).
7. V. G. Dubinchuk, *Physico-Mathematical Models of Interpretation of the Data of Isotope-Indicator Testing of Ground Water* [in Russian], Moscow (1983).