Potential radiation impact of the burial of the "Klivazh" facility on the Yunkom mine

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Received: December 010, 2020 | Revised: December 19, 2020 | Accepted: December 31, 2020

DOI: 10.5281/zenodo.4538369

Abstract

Today, the issues of assessing natural and man-made risks in the area of the Joint Forces operation related to the flooding of the mine by Yunk are relevant. The risks of groundwater contamination and groundwater with radionuclides from the "Klivazh" facility, which was formed as a result of an underground nuclear explosion, increase in the absence of the pumping possibility of mine water from this mine. Radiation threats caused by the passive flooding of this facility create a number of negative consequences for the territories controlled by Ukraine. Therefore, there is an urgent need to assess the risk of contamination of the surrounding areas with radionuclides cesium-137, strontium-90 from the "Klivazh" facility. Given the existing hybrid war in eastern Ukraine, the solution to this problem can be considered as an element of analytical assessment of the predicted consequences of the "environmental war" against Ukraine.

Key words: the ecological and geological environment, nuclear explosion, groundwater, contamination, the geological conditions, migration of radionuclides.

Introduction

Amid the closure of mines in Donbas, the ecological and geological environment responds with "auto-rehabilitation processes". These have considerable effects on conditions affecting urban mining agglomerations. Key processes include a regional rise in groundwater levels within affected river basins. There is also an accelerated migration of anthropogenic contamination due to an intensified water exchange in the zones of aeration (also known as unsaturated zones or zones of suspended water). There is an expansion of waterlogged and flooded areas of geochemically contaminated sites, both under and above ground.

Additional rock subsidence during rock saturation with water and the development of new migration routes for explosive gases may to a great extent be qualified as auto rehabilitation processes. These are also occurring in connection with the closing of mines in the coalmining Donetsk region.

Analysis of recent research and publications

In 1979, an industrial underground nuclear explosion with a TNT energy equivalent yield of 200–300 tonnes (0,2– 0,3 kt) was produced at the Yunkommine. This mine is in Yunokommunarovsk town, on the southeastern periphery of the Tsentralnyi coalmining district in Donetsk region. This happened for the first time in the world and in a densely populated and intensively exploited coalmining district. The purpose of the underground nuclear explosion was to assess its effectiveness for reducing the frequency of sudden coal and gas outbursts in the process of coal bed workings. A code name for the section of the geological environment containing the chamber of the underground nuclear explosion and an adjacent jointing zone is the “Klivazh” facility (Figure 1).

In the opinions of the researchers of the present report, the planned closure of a group of hydraulically interconnected mines of the Central coalmining district, including the ‘Yunkom’ mine, given insufficient physical and technological coherence of measures, creates a risk of practically uncontrolled flooding of the “Klivazh” facility. The consequences of this are difficult to predict precisely but may include the contamination of groundwater and the wider geological environment with anthropogenic radionuclides. This may lead to a risk from radiation to human health and life.

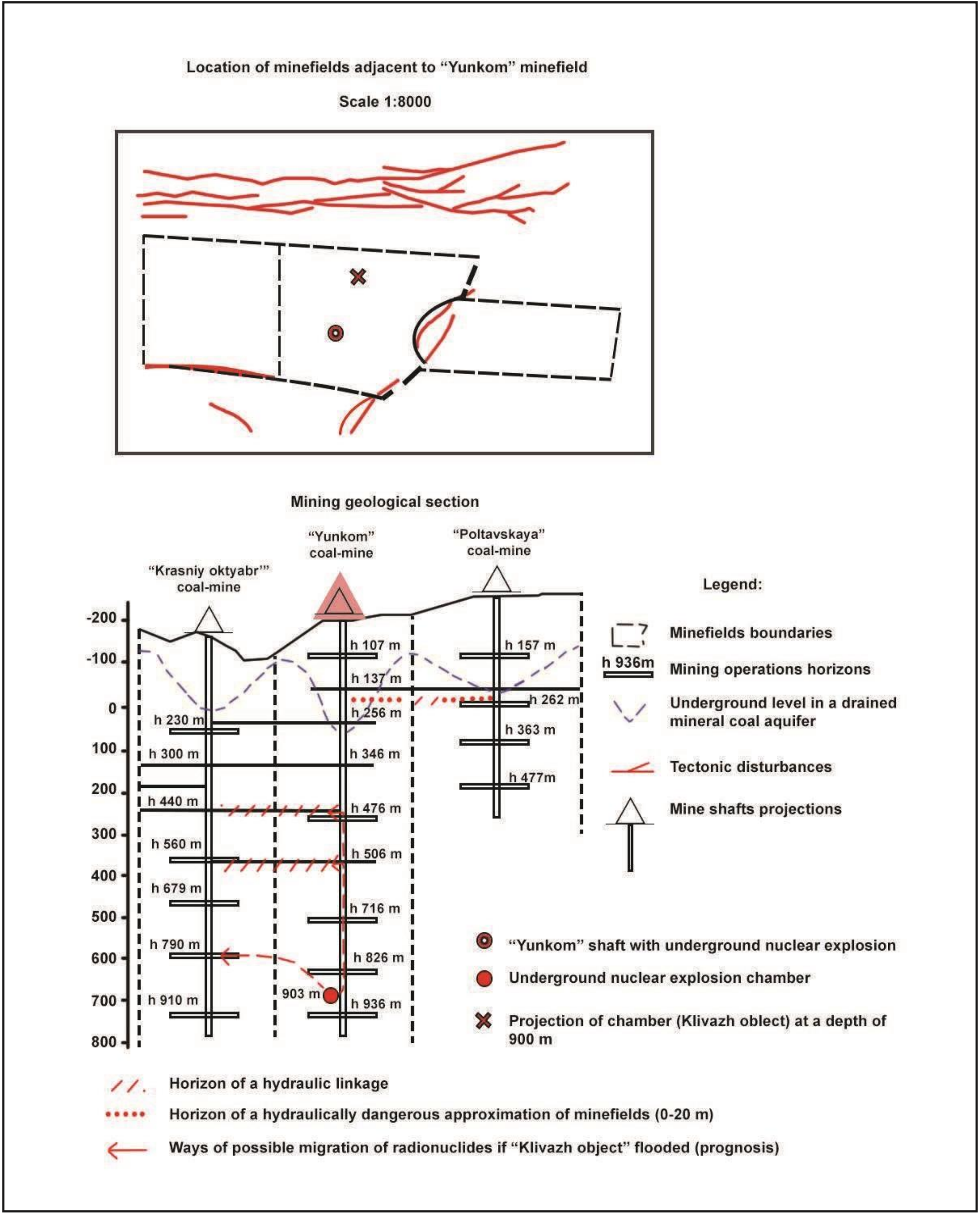

Figure 1 – The ‘Yunkom’ mine area: adjacent minefields and a geological section

Results and discussion

Groundwater contamination from the 'Yunkom' mine

The 'Yunkom' mine is a hydraulically interconnected area of the geological environments of the adjacent Chervonyi Zhovten and Poltavska mines. Groundwater contamination has been persistent here for the past 50 years, extending as mining operations have extended in depth and area. Key impacts include the enhanced infiltration of saline mine water, geochemical contamination of landscapes, and destruction of regional low-permeability layers. This has resulted in a practically complete replacement of fresh water (up to 1,0–1,5g/ dm^3) and slightly saline water (1,5–3,0g/dm^3) with saline water containing concentrations of dissolved salts in the range of 3–5g/dm^3 in up to 70% of the research area.

Various previous project studies demonstrate that accelerated groundwater contamination during the development of mining operations was caused by an increasing impact of the following factors.

A rise in rock massif permeability due to the development of anthropogenic jointing in the areas where rock balance has been upset by mining operations.

A rise in the infiltration of anthropogenic water and contamination caused by a more active interplay of surface and ground water, including due to the undermining of river beds.

An increase in the area of landscapes contaminated through human activity, as well as in the number of filtering waste ponds with industrial and mine water.

Development of poor drainage areas and non-contributing areas where land subsides over mine workings.

The vulnerability of groundwater has been assessed in quasi- stationary conditions when it is affected by mine water drainage, tectonic structures, a hydrographic network and a zone of aeration (groundwater depth levels). These assessments have demonstrated the prevalence of areas with a high level (60%) and an elevated level (30%) of proneness for aquifer contamination amid landscapes creation and changes induced by industrial activities.

Presently, in the area of declined groundwater levels of the 'Yunkom' minefield within the confines of finished coal layers and the surrounding permeable sandstone, there is a possibility of an accelerated upward migration of saline mine water, including radionuclides of caesium-137 and strontium-90, during the flooding of mine workings. This may happen if there is a passive flooding and a partial decline in the level of hydro-isolation of the "Klivazh" facility while preliminary safeguarding measures to stabilise the adjacent rock massif are not implemented.

An analysis of the mining-geological conditions of the Chervonyi Zhovten and Poltavska mines, which are adjacent to the 'Yunkom' mine, demonstrates that the presence of hydraulic linkages may be a contributing factor for the acceleration of upward and planned radionuclide migration processes. Key links are the horizons of 476m and 596m, and the hydraulically hazardous approaching of mine workings (the horizon of 262m of the Poltavska mine – the 'Yunkom').

The explosion chamber of the "Klivazh" facility is located in the central area of mining operations of the 'Yunkom' mine, which is characterised by an utmost disturbance of coal-bearing rock massif and a significant depth of mine workings (up to 1 km). Thus, if there is an accelerated hydro- geo-mechanical destruction of the Klivazh facility and the facility is upwardly flooded, there will be an increased risk of the manifestation of all groundwater vulnerability factors, as well as local contamination of surface watercourses.

On the other hand, the explosion chamber of the "Klivazh" facility is located at a substantial depth (903m) and characterised by the local evolution of jointing and the absence of hydraulic linkages and hazardous geotechnical approximations with mine workings of the adjacent mines (the Chervonyi Zhovten mine and the Poltavska mine). There is also a slow rock deformation and low rates of the migration of water-soluble forms of radionuclide, namely caesium-137 and strontium-90, through a relatively solid layer of rock capable of absorption.

In addition, the flooding of a stabilised rock massif, provided there is a steady filtering saturation of the explosion chamber of the "Klivazh" facility with water, may lead to the establishment of a practically stagnant regime. This may result in decelerated sorption and migration processes in the enclosing rock.

The underground nuclear explosion at the 'Yunkom' mine

The 'Yunkom' mine (within the Central coalmining district) in Donbas was distinguished by high levels of sudden outbursts of coal and explosive gases during mining operations. Between 1959 and 1979, there were up to 235 gas-related geodynamic phenomena at the 'Yunkom' mine, including 28 cases involving the death of workers.

The geological conditions of the 'Yunkom' minefield feature an intensive tectonic disturbance of rock by four large thrusts and a dense network of local deformations of coal seams and enclosing rock. On average, there is one disturbance per 243 m of the minefield. At the horizon of 823m, up to 42% of coal beds that are worked are located in the areas of geological faults. High gas saturation levels of coal-bearing rock under conditions of significant tectonic disturbance is a factor contributing to the continuous emergence of gas and coal outbursts and a growing insecurity of mining operations.

The nuclear explosion with a yield of 200-300 tonnes (0,2-0,3 kt) was conducted at a depth of 903m between the 'Deviatka' and the 'Kyrpychivka' coal seams, 45m and 31m away, respectively. The chamber for the placement of the nuclear explosive charge was constructed in an inclined working, which had been driven from the level of 826m through enclosing sandstone. The place of the explosion chamber in sandstone was selected on the basis of expectations for the formation of a vitreous water-insoluble melt capable of containing up to 95% of the explosion products, according to estimates. In addition, to prevent the migration of gaseous explosion products, the explosion chamber was isolated by concrete bulkheads with a width of 6–10 m.

Justifying the explosion's yield, the designers factored in seismic safety of mine shafts, permanent mine workings, and industrial and residential buildings located on the surface in the area close to the 'Yunkom' mine and the town of Yenakiieve. After the explosion, up to 1,260 buildings were examined on the surface, within a radius of 1,6km from the explosion epicenter. Of the examined buildings, 22 (1.8%) demonstrated the emergence of hairline cracks, the deformation of chimneys and the falling-off of whitewash. Practically no disturbances were identified in mine workings, apart from the falling-off of small fragments in a long wall working from the roof and side surfaces of individual nearby workings.

The examination results demonstrated that gaseous explosion products had not migrated beyond the confines of the isolating bulkheads, since the traces of strontium-90 and caesium-137 emerged in mine water only after the opening of the isolation-complex material in 1991. Between 1979 and 1992, there was no registration of any accident associated with a sudden outburst of coal and explosive gases.

Mining operations in the area of potential gas-geodynamic impact of the nuclear explosion were conducted in accordance with a special project. The project envisaged a procedure for preparing and working with coal seams, as well as measures concerning radioactive safety and environmental protection. According to agency-level data for 1992–2001, radiation pollution levels of the workings and the surface corresponded to the natural background level, while radionuclide concentrations of strontium-90, caesium-137 and tritium in mine water were lower than acceptable levels for drinking water by a factor of hundreds.

Preliminary ecological-geological assessment of the nuclear explosion chamber and the adjacent rock massif

An ecological-geological singularity of the formation of the nuclear explosion's affected area is the presence of an explosion chamber (a camouflet chamber), i.e. a chamber that has evolved without an explosion-driven outburst of rock. Field assessments have showed that vitreous sandstone melt may contain concentrations of up to 95% of radioactive explosion products (Semypalatynsk, Nova Zemlia, and other nuclear test sites).

Data obtained through probing boreholes and an inspection of the 936-metre horizon on 17 October 2001 indicate the following radio-ecological conditions in the explosion chamber of the "Klivazh" facility.

Partial downward filtration of groundwater into mine workings at the horizon of 936m (33m below the explosion epicenter).

Destructive deformations of the explosion chamber and water admission (according to the data obtained through a probing borehole, which opened the chamber in September 1991).

A small horizontal radius of the explosion chamber – up to 5,0m (diameter up to 10,0m), with the formation of up to 100 tonnes (according to estimates) of a vitreous molten mass where 95% of radioactive explosion products are concentrated.

Formation of an area of crushed (entirely ruined) rock, within the confines of which such rock is transformed into sand fractions and gravel fractions, with a radius of up to 8,0m from the explosion epicenter, i.e. with a stable area thickness of (8,0-5,0)≈3,0m.

Development of a radial jointing area at a distance of up to 15m from the explosion epicenter or in the adjacent rock massif with a thickness of (15-8,0) ≈ 7,0m.

It is estimated that individual activated (formed) hidden fractures may appear at a distance of up to 20–25m from the explosion epicenter. Meanwhile, according to the data obtained through 23 probing boreholes, no radioactive melt residues have been detected in the radial jointing area.

Estimated radiation contamination in the explosion chamber and adjacent rock massif

Studies conducted in the process of underground nuclear explosions have established that one hour after an explosion (t=1 hour) the volume of radioactive contamination (R_t) depends on the yield of such explosion (TNT equivalent in kilotons) *q*:

$$R_{t=1h} = 4.5 \ 10^8 \ q = 4.5 \ 10^8 \ 0.3 = 1.35 \ 10^8 \ Ci$$

Generally, the quantity of radioactive products R_t changes over the course of time and is a function of the following:

$$R_t = R_{t=1\,h} \, t^{-1.2}$$

Within the period of 1979–2001, the residual quantity of radioactive products may be estimated at the following level:

$$R_{t(2001)} = \frac{R_{t=1ч}}{[(2001-1979)\times 365 \times 24]^{1.2}} = \\ = \frac{1.35\times 10^8}{(1.93\times 10^5)^{1.2}} = 60Ci$$

Certain estimations imply that, depending on the composition of a nuclear explosion substance, the volume of produced radioactive products may amount to the following: $R_0 = 2 \ 10^6 Ci$ when $q = 1 \ kt$. This means that, at the initial stage for the conditions of the 'Yunkom' mine this could amount to:

$$R_0 \cong 2 \ 10^6 \ 0.3 \cong 0.6 \ 10^6 \ Ci$$

In this case, the residual volume of radioactive residues in the explosion chamber as of 2001 may amount to the following:

$$R_{2001} = \frac{R_0}{t^{1.2}} = \frac{0.6\times 10^6}{(1.93\times 10^5)^{1.2}} \cong 0.3Ci$$

A control calculation of residual radio activeness associated with the presence of caesium-137 and strontium-90 in the vitreous melt ($P \overset{\sim}{=} 10^5 kg \overset{\sim}{=} 100$ *tonnes* with the chamber volume of $V = 500m^3$) produces the following result (according to the data of the Russian Design and Research Institute of Industrial Technology of the Atomic Energy Ministry of the Russian Federation, 1992).

Specific activity of the vitreous melt in the explosion chamber of the "Klivazh" facility for strontium-90 amounts to:

$R_{90} \cong 6.2 \ 10^{-5} \ Ci/kg \ (2.3 \ 10^6 \ Bq/kg)$;

Specific activity for caesium-137 amounts to:

$R_{137} \cong 4.6 \ 10\text{-}5 \ Ci/kg \ (1.7 \ 106 \ Bq/kg)$;

The total volume of radioactive contamination for caesium-137 and strontium-90 will amount to:

$$R_{(90)+(137)} \cong (6.2 + 4.6) \ 10\text{-}5 \ Ci/kg \times 10^5 \ kg \cong 10.8 \ Ci$$

The presence of other long-lived radioactive explosion products in the explosion chamber (plutonium-239, americium-241 and others) demonstrates that the estimation of residual contamination at the level of $R_{2001} \cong 60$ Ci is realistic.

In conclusion:

1. The available data suggest that the ecological-geological state of the "Klivazh" facility under current conditions is characterised by relative stability and probability of a slow filtration transition of the solid (continuous) stream of groundwater through the area of the explosion chamber, crushed and radially jointed rock in the direction of the 936-metre horizon.
2. Prevalence of permeable sandstone in the geo-mechanical impact area of the nuclear explosion (up to 75.4% in 135m of rock massif) diminishes the hydro-isolation capacity of the rock massif as further deformations develop and the rock massif becomes fully saturated with water during mine flooding.
3. The affected area of the "Klivazh" facility is characterised (under the current conditions of incomplete water saturation of the rock massif) by a limited migration of radioactive explosion products due to their predominant concentration in vitreous formations of low solubility in the explosion chamber and the sorption impact of low- permeability coal-bearing rock.

Migration of radionuclides during the 'Yunkom' mine closure, 'dry' and 'wet' abandonment

Key factors contributing to environmental vulnerability under different mine-closing scenarios.

In our opinion, the following key factors may account for a decline in the protective ability of the geological environment.

Hydraulic linkages of the 'Yunkom' mine with the adjacent Chervonyi Zhovten mine (the horizons of 476m and 596m) and the Poltavska mine (the horizon of 262m), as well as the presence of horizons where mine workings approach each other, creating geo-technical hazards.

Great tectonic disturbances on the border of the 'Yunkom' mine, which are characterised by reduced geo-mechanical rock stability, and accelerated migration of groundwater.

Abutting of the Yunokomunarivska industrial urban agglomeration to the technical borders of the 'Yunkom' mine. In our opinion, this may contribute to the emergence of additional factors of geological environmental vulnerability: the presence of waterlogged areas with reduced rock stability, increased groundwater aggressiveness, and other factors.

High spatial and temporal variability of regional groundwater levels during mine closure brings about a possibility for a stochastic development of the affected area of the "Klivazh" facility of the 'Yunkom' mine. Therefore, below we consider major characteristics of 'wet' and 'dry' abandonment conditions for the "Klivazh" facility in the mining space of the 'Yunkom' mine.

Risk estimates for 'dry' abandonment of the 'Yunkom' mine.

The explosion chamber at the "Klivazh" facility is centred at a depth of 903m in a layer of sandstone. As estimated by use of boreholes, the nuclear explosion chamber has a radius of 5m and a total capacity of approximately 500m^3. It holds 100 tonnes of vitreous melt containing 6.2 curies (Ci) of strontium-90 and 4.6 Ci of caesium-137 while potential maximum contents of radiation products total up to 60 Ci (see Figure 4).

Strontium-90 is the most mobile radionuclide and thus it is reasonable to compare the balance of strontium migration distribution with mine water contamination levels in 1989 (4.0 10^{-13} Ci/l) and 2001 (5.1–9.4 10^{-13} Ci/l). The level of sludge contamination in the mine pond (as the final destination) is (0.58–3.3) 10^{-10} Ci/l. The level of caesium-137 contamination during this time remained practically unchanged: 8.0 10^{-13} Ci/l in 1989, and (7.6–9.7) 10^{-13} Ci/l in 2001.

Unfortunately, there are no assessments of the levels of radiation contamination of mine water and sludge in direct outflows from the explosion epicentre area. Therefore, we assume that there is a complete efflux (with a minor rise in the period of 1989–2001) of the water-soluble phase of strontium-90 along with mine drainage water (for the period of 1979– 2001, or 22 years with an average yield of 450m^3 per hour) and that its sorption concentration occurs in the sludge layer with a width of up to 200 mm (with an accumulation speed of 10 mm per year).

With the help of the above data, we may make the following rough calculations concerning the strontium-90 balance and distribution. Assuming strontium-90 has been arriving in the mine pond steadily, we may calculate the total efflux of strontium-90 in 22 years as follows (an average concentration of 7 10^{-13} Ci/l):

$$R_{90} = 450 \times 24 \times 365 \times 22 \times (7\ 10^{-13} Ci/l) \approx 0.06\ Ci$$

Calculation results demonstrate that the migration efflux amounts to (0.06/6.2) 100% ~= 1.0% of the initial amount of strontium-90 in the explosion chamber. In the same period, resulting from a radioactive decay, the amount of strontium in the chamber has fallen by (lg22/lg28) 50% ≈ 37% or nearly by one third. With the help of the above estimates, we may also conclude that the radioactively contaminated explosion chamber is sufficiently isolated and that the efflux of strontium-90, which is the most capable of migration, is very slow, at nearly 100 times less than its physical decay.

With conditional strontium-90 accumulation in the bottom sludge layer with a width of 200mm (0.20m) and an average concentration of 2 × 10^{-10} Ci/kg, the level of contamination of a conditional area with a size of 1 km^2 will amount to the following (given sludge density of 1.1kg/dm^3 = 1,100 kg/m^3):

$$R_{90/1km^2} = 10^6\ m^2 \times 0.20\ m \times 1.1 \times 10^3\ kg/m^3 \times 2 \times 10^{-10}\ Ci/kg = 4.4 \times 10^{-2}\ Ci/km^2$$

The estimated level of strontium-90 contamination density is nearly twice as large as the average global level of strontium- 90 distribution in the topsoil as of 1986 (0.02 Ci/km^2).

The ratio of strontium-90 concentrations in the mine pond and in the sludge may be regarded as an indication of their even distribution, which amounts to the following:

$$K_p = \frac{(0.58 - 3.3) \times 10^{-10}}{(5.1 - 9.4) \times 10^{-13}} = (1.1 - 3.5) \times 10^2$$

This means that it corresponds to the values whose distribution is known from literary sources (*n* 10^0 – *n* 10^2).

The below rough calculation of a potential seepage-water contamination level (4m^3 per hour) as a proportion of its mixture with the general mine drainage water (450m^3 per hour) may be indicative of the current relative stabilisation of radio-ecological and hydro-geological parameters for radionuclides migration and sorption in the rock massif of the affected area of the explosion chamber:

$$R_{поч} = R_ш\left({}^{450.0}/_{4.0}\right) \equiv 10^2 R_ш$$

Given the above data, the level of potential radioactive contamination of seepage water at the edge of leakage from the affected area of the explosion chamber may reach the following amounts:

for strontium-90 – (5.1–9.4) 10^{-11} Ci/l
for caesium-137 – (7.6–9.7) 10^{-11} Ci/l.

Compared to acceptable concentrations of these two radionuclides in drinking water (allowable concentration for the population) according to the 97 Radiation Safety Standards for Ukraine (the NRBU-97) [4], the initial contamination may amount to the following:

for strontium-90 – (5.1–9.4) 10^{-11} Ci/l: 2.7 10^{-11} = 1.9–3.5 times;
for caesium-137 – (7.6–9.7) 10^{-11} Ci/l: 2.7 10^{-9} = 0.03–0.04 times.

A tritium contamination level at the beginning of tritium arrival in mine water may be estimated according to the data for 1991 obtained through probing boreholes #1 and #2 (1×10^3 and 8.5×10^3 Bq/l, or 2.7 10^{-8} Ci/l and 2.1 10^{-7} Ci/l). Comparing it to an allowable concentration according to the NRBU-97, (30,000 Bq/l or 8 10^{-7} Ci/l), we obtain the following values:

$$(0.27\text{-}2.1)\ 10^{-} : 8\ 10^{-7} = 0.03\text{–-}0.26\ times.$$

The above estimates imply that, even when compared to more stringent standards of the NRBU-97, the level of initial contamination of seepage water in the explosion chamber with the most toxic radionuclides in the area of their arrival in the general mine drainage water does not exceed acceptable values. A certain increase in strontium-90 concentrations in seepage water may have a very limited duration due to rapid dilution in increasing volumes of water drainage, which at a horizon of 936m (deeper than the explosion chamber) grows by 8–10 times (up to 40–45m^3 per hour).

Conclusions for "dry" abandonment conditions

1. The data obtained from various sources indicate a relatively balanced current state of the explosion chamber of the "Klivazh" facility at the Yunkom mine and virtually a lack of preconditions for an increase in its radio-ecological hazard level.
2. According to the estimates, application of the 'dry' abandonment scheme for the "Klivazh" facility, given its location in a relatively stable massif of monolithic sandstone, will help to maintain the achieved balance and will contribute to the sorption containment of a predominant part of radiotoxic nuclides of caesium-137, strontium-90 and tritium, as well as hydro-geo-mechanical strength of the explosion chamber. Under the given conditions, the speed of radionuclides' physical decay exceeds their migration efflux by nearly two orders of magnitude. When necessary, as a supplementary safeguard measure, it may be proposed to fill the space of the explosion chamber with zeolite gravel or perlite, as a mechanically stable filler and sorbent.

There is a possibility of the emergence of additional deformations in the explosion chamber resulting from stress re-distribution in the adjacent finished coal seams. This brings about a need for expanding the radio- ecological monitoring system, developing a set of the "Klivazh" facility models (nuclear-physical, geo-mechanical and sorption-filtration) and urgently conducting a comprehensive radio-ecological inspection of potential radionuclide migration routes with balance calculations of radionuclide distribution in the environment.

Conclusions

1. Geomechanical impact of a nuclear explosion (at the "Klivazh" facility) led to a decrease in the total waterproofing water saturation of the rock mass of permeable sandstones (up to 75.4% in 135 m thick rocks), in the conditions of further deformations during the flooding of the mine.
2. The need to expand the system of radioecological monitoring, development of models set the object "Klivazh" (nuclear-physical, geomechanical, sorption-filtration) and urgent implementation of a comprehensive radioecological survey of potential migration routes of radionuclides with balance calculations of their distribution in the environment, deformations of the explosive chamber due to the redistribution of stresses from adjacent spent coal seams.
3. Ecological and hydrological assessments indicate that the potential closure of one or a group of hydraulically interconnected mines of the Central Coal Mining District, including the mines of the Horlivka mining and urban agglomeration and the 'Yunkom' mine (underground nuclear explosion zone at a depth of 903 m ("Klivazh" facility) creates a risk of environmental emergency in the most densely populated part of Donbas.
4. Lack of experience in the world practice of flooding and flooding of industrial and urban agglomerations with high levels of radiation contamination of soils is of practical interest to the existing problem, which is a fundamental novelty in ecological, man-made, and social plans.

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