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# Radionuclide dispersion from a waste burial in the geosphere

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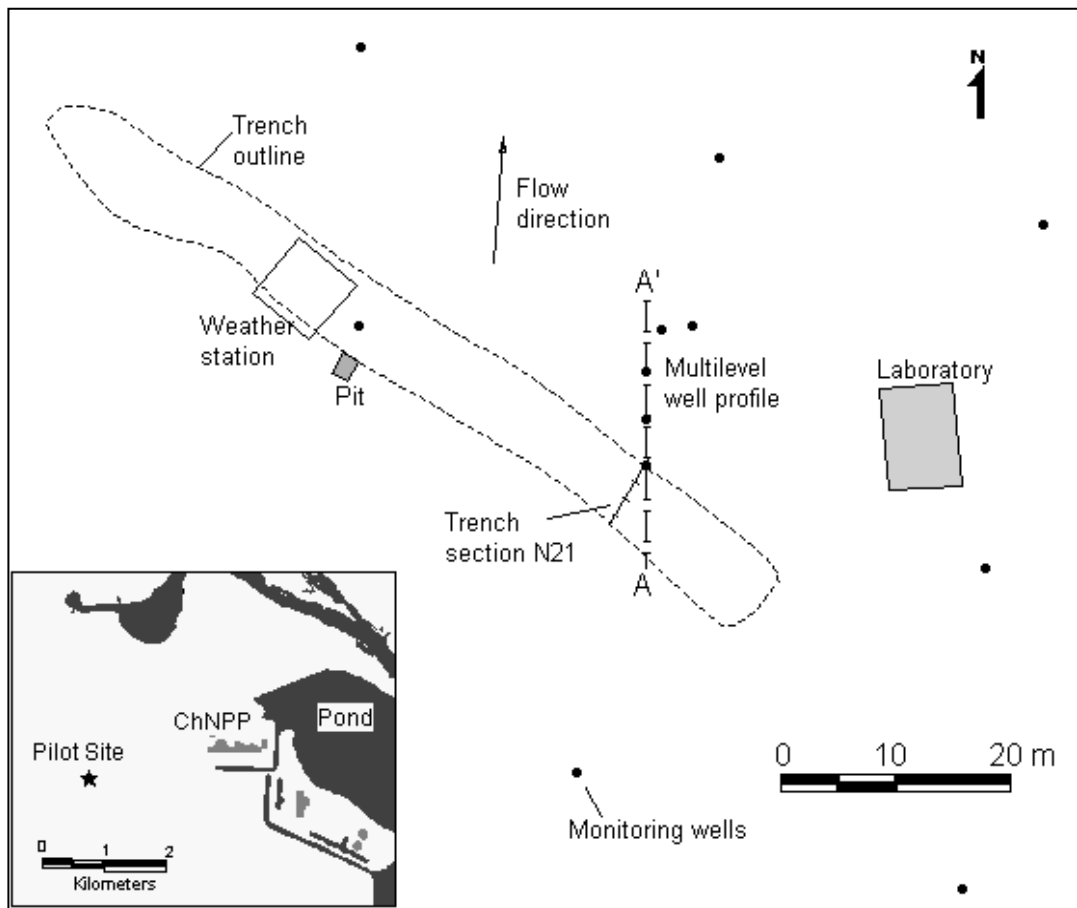
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**Abstract:** Results are presented from the ongoing international study, namely Chernobyl Pilot Site Project, aimed at characterization and modeling of process controlling  $^{90}\text{Sr}$  releases from the shallow trench at Chernobyl NPP site containing nuclear fuel particles and subsequent radionuclide transport in the underlying eolian and alluvial sand aquifer. Microscopic analyses of fuel particles separated from waste have identified two families of particles: U–O and Zr-U-O (~25% and 75% of the number of particles respectively). The Zr-containing particles exhibits low dissolution rate, therefore radionuclide inventory in source term available for migration is significantly less than estimated before. The  $^{90}\text{Sr}$  migration velocity in the eolian sand layer is estimated at  $\approx 7\%$  of real groundwater flow velocity ( $K_d \approx 3$  ml/g). Alluvial sediments comprising the middle part of the aquifer have notably higher sorption capacity ( $K_d \approx 10$  ml/g). Radioactivity balance calculations show that 4 - 7% of initial trench inventory of  $^{90}\text{Sr}$  has migrated by now to the geo-environment. Obtained results have important implications on safety assessment and remedial analyses of the radioactive waste dumps at ChNPP. In particular, local geological barriers and hydrogeological settings are shown to provide “natural containment” of contaminated groundwater essentially limiting off-site transport of  $^{90}\text{Sr}$  to the hydrographic network.

## 1. INTRODUCTION

The waste dump sites created in 1986-87 during emergency clean-up activities at Chernobyl Nuclear Power Plant (ChNPP) contain about  $10^6$  m<sup>3</sup> of low-level wastes [1-3]. These waste dumps largely do not satisfy regulatory requirements to engineered low-level waste near-surface disposal facilities and pose radiological risks to the environment. Of particular concern is hydrogeologic migration of strontium-90 ( $^{90}\text{Sr}$ ), which shows high mobility in soils and groundwater system. As pointed out in the appraisal by the Nuclear Energy Agency Committee on Radiation Protection and Public Health [2] “all these waste are potential source of contamination of the groundwater which will require close monitoring until safe disposal into appropriate repository is implemented” and that “large uncertainties remain which require a correspondingly large characterization effort”. Need to develop rationale risk-based long term waste management and remediation strategy for Chernobyl waste dump sites is recognized by the Ukrainian authorities as a priority problem [3].

At the same time, from the point of view of a radioecology scientist the Chernobyl site can be considered as a large scale “laboratory at open sky” providing unique opportunities to explore behavior and fate of fallout radionuclides, and to develop and validate modeling approaches and techniques for radionuclide transport in the environment.



**Figure 1.** Map of the Chernobyl Pilot Site.

From 1998 the behaviour of radionuclides is being studied jointly at the waste site near the ChNPP (i.e., Chernobyl Pilot Site; Fig.1) by the Institute for Nuclear Safety and Protection (IPSN) and the Ionising Radiation Applications and Metrology Department (DAMRI) of the Atomic Energy Commission in France, and by the Institute of Agricultural Radiology (UIAR) and the Institute of Geological Science (IGS) in the Ukraine. As discussed above, this study (namely Chernobyl Pilot Site Project) is of prime importance for the Ukrainian institutes in the perspective of practical risk assessment and waste management issues. The project is equally important for the IPSN, as the Chernobyl Pilot Site provides it with experimental field facility for on-site validation and development of the theoretical models used by the institute in its various radiological impact studies to represent the migration of radioactive contaminants in soils and near-surface geological environment.

The main processes involved in radionuclide transport from the waste site to the surrounding environment give rise to two major lines of research. Firstly, the Chernobyl Pilot Site Project is focused at the study of the dissolution mechanisms of fallout fuel particles and geochemical interactions between the soil and the dissolved radionuclides, and secondly, on the study of the hydrodynamics of water and associated dissolved radioactive elements transport in the in the unsaturated zone and in the aquifer underlying the waste burial.

The project is scheduled for 1999 – mid 2003 and comprises three main stages: (1) the site characterisation involving collection and analysis of radiological, hydrogeological and geochemical data; (2) development of a set of sub-models and global model of the waste site, and planning of model validation (confirmation) experiments, and (3) setting up, carrying out and interpretation of model validation tests.

Below some results of the characterization phase of the project are reported. The characterization works have targeted among others the following key issues:

- microscopic study of properties and dissolution mechanisms of reactor fuel particles comprising source term of the migration;
- global characterization of the source term (trench) geometry and radioactivity inventory;
- development of conceptual geology - ground water flow model of the waste site;
- derivation of geostatistical model of the aquifer and assessment of parameters of solute dispersion in the subsurface environment;
- characterization of strontium-90 distribution and interaction with the aquifer sediments.

Obtained information and data provide new insights into process controlling  $^{90}\text{Sr}$  releases from the trench and subsequent radionuclide transport in the underlying sandy aquifer, and have a number of important implications to safety assessment and remedial analyses of the radioactive waste dumps at ChNPP.

## 2. CHERNOBYL PILOT SITE

The study site is located 2.5 kilometers south west of the ChNPP in the so-called “Red Forest” radioactive waste dumpsite. In 1987 in the course of clean-up works radioactive materials, made of topsoil layer and contaminated tree trunks from the dead pines “red forest” killed by extreme radiation levels in 1986, have been bulldozed *in-situ* in a few meters deep trenches [1].

A particular waste burial (trench no.22-T), namely Chernobyl Pilot Site (CPS), was selected since 1998 by the joint French- Ukrainian scientist team for radiological characterization and monitoring studies reported below. The burial represents ~70 m long, 8-10 m wide and 2-2.5 m deep unlined trench (see Fig.1). The source term of radionuclide migration to the environment is a heterogeneous mixture of contaminated organic materials and soil containing micron-size reactor fuel particles. The specific activity of  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$  in waste is  $10^5$ - $10^6$  Bq/kg.

The geologic section of CPS consists of the sequence of sedimentary layers of Quaternary eolian and alluvial sands with beds of sandy loam material. The depth to groundwater table is 1-3 m. The unconfined sandy aquifer is bounded at a depth of 30 m by a low permeable Eocene marl layer. Average annual rainfall is 550-650 mm, while infiltration recharge rate to aquifer is estimated at  $150$ - $250$  mm.y<sup>-1</sup>. For 14 years following disposal, radionuclides have been leached from the trench by meteoric water, and have been penetrating the underlying unsaturated soil and the aquifer. As a result,  $^{90}\text{Sr}$  concentration in groundwater in the upper part of the aquifer in the vicinity of the trench varies between  $n \times 100$  and  $n \times 10,000$  Bq/l, and the radiostrontium plume has spread some 10 m downstream from the source [4, 5].

In the course of the project the CPS was equipped by series of piezometers and multilevel observation wells to the aquifer, ceramic moisture samplers to unsaturated soil profile, on-site laboratory facility, automated weather station and special pit instrumented with sensors for monitoring moisture flow and radionuclide transport process in the unsaturated zone (see Fig.1).

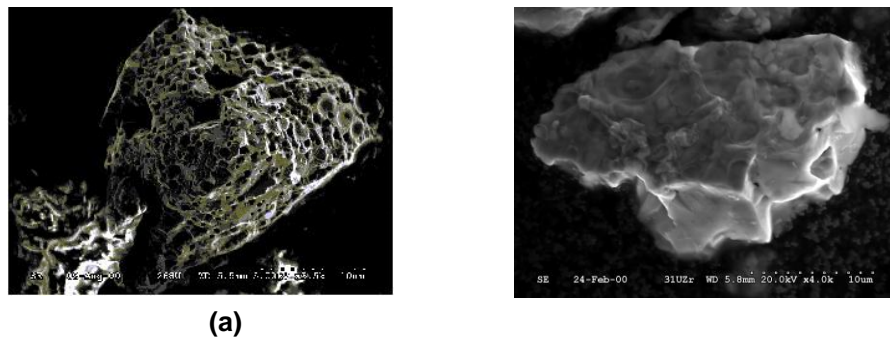
### 3. RADIONUCLIDE MIGRATION SOURCE TERM

#### 3.1. Microscopic features and characteristics of nuclear fuel particles

Chernobyl fallout radionuclides were initially associated with micron-size dispersed nuclear fuel “hot particles” [6, 7]. In order to quantify the source term of migration, it is necessary to determine the physical and chemical characteristics of fuel particles and their dissolution rates.

Scanning Electron Microscopy (SEM) was applied for visualization, determination of size, geometry, and chemical composition of particles separated from the CPS waste. The methodology is described in [8]. In total 568 hot particles (mean diameter of 4.2  $\mu\text{m}$ ) were separated from trench material by sedimentation in heavy liquid (bromoform). Based on estimation of activity of waste before and after fuel particle separation, it was estimated that by year 2000, about 70% of  $^{90}\text{Sr}$  activity in trench is associated with fuel particles. The most important finding is that source term consists of two types of fuel particles:

- 1) composed of uranium (U) and oxygen (O), and
- 2) composed of U, O and zirconium (Zr).



**Figure 2.** Microphotographs demonstrating typical morphology features of UO<sub>x</sub> (a) and Zr-U-O (b) matrix fuel particles isolated from trench waste material.

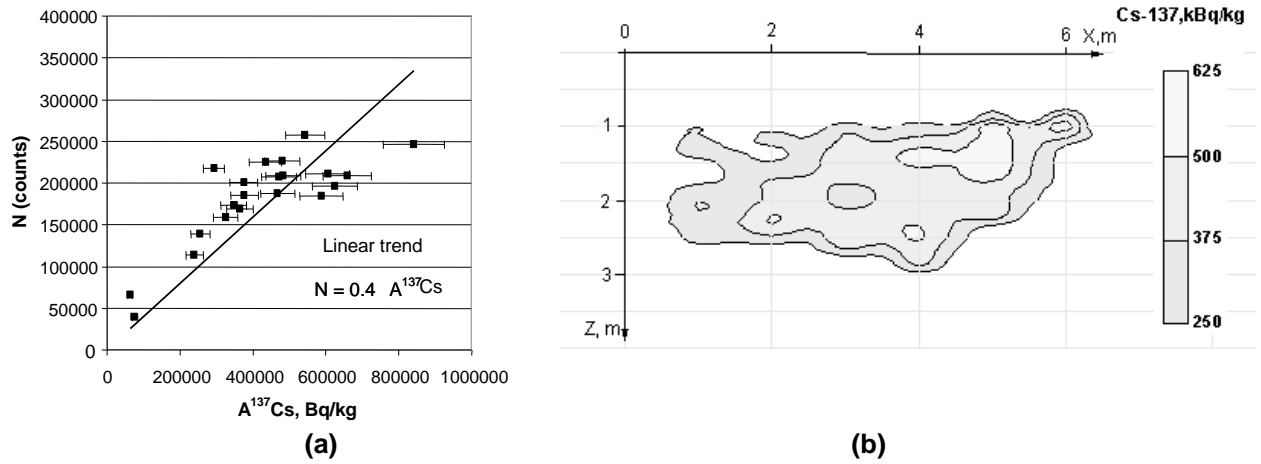
U-O-Zr particles account for 75% of the source term. SEM showed that U-O particles have significant secondary porosity due to chemical weathering, while Zr-U-O particles demonstrate much higher stability (Fig.2).

The Chernobyl fallout dissolution models developed before (e.g., [6]) considered that the source term is only U-O particles. However, according to new data in case of CPS significant portion of activity in the trench will likely remain “bound” to Zr-U-O particles and therefore unavailable for migration process for long time.

#### 3.2. Radionuclide inventory of within the trench

Back in 1987 in difficult radiological conditions creation of trench no.22-T by Soviet Union civil defense troops has not been accurately documented. To characterize distribution and inventory of radioactivity within the trench the following methodology was developed. Boreholes were drilled on a mesh through the trench body, and *in-situ* measurement of  $\gamma$ -emission profiles in boreholes were done using submersible counting probe. Next specific activity of  $^{137}\text{Cs}$  in soil was estimated using empirical correlation equation (Fig.3-a) between radionuclide content in soil ( $A_{\text{Cs},i}$ , Bq/kg) and  $\gamma$ - count rate (N, number of counts per 10 seconds):

$$A_{\text{Cs},i} = \Gamma \times N, \quad \Gamma = 2.5 \pm 1 \text{ Bq (kg.count.s}^{-1}\text{)}^{-1}.$$



**Figure 3.** Estimation of  $^{137}\text{Cs}$  distribution in trench. (a) - Empirical relation for estimation of  $^{137}\text{Cs}$  activity in waste from number of  $\gamma$ -counts; (b) – Derived  $^{137}\text{Cs}$  distribution in trench cross-section N21 (see Fig.1 for cross-section location).

Example distribution of  $^{137}\text{Cs}$  activity in trench cross-section is shown at Fig.3-b. Spatial integration of about 2000 individual activity measurements in boreholes results in the following integral estimate of  $^{137}\text{Cs}$  activity in the trench (for 2000):

$$A_{\text{Cs}} = 600 \pm 240 \text{ GBq.}$$

Inventory of other fission products was estimated using empirical “correlation” between radionuclide activity ratios for trench material and for Chernobyl fuel particles [7]. Direct correlation between  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$  activity in trench is relatively poor, because  $^{90}\text{Sr}$  has been re-distributed inside and outside the trench due to hydrologic migration process. Therefore two-step approach was developed. First  $^{154}\text{Eu}$  content in trench was estimated using experimental ratio of activity  $^{137}\text{Cs}/^{154}\text{Eu}$  for the waste at CPS ( $R_{\text{Cs-Eu}}^{\text{TR}} = 145$  for 2000):

$$A_{\text{Eu}} = A_{\text{Cs}} / R_{\text{Cs-Eu}}^{\text{TR}} = 4 \pm 1.6 \text{ GBq.}$$

Europium is relatively immobile radionuclide, which was associated mainly with the fuel matrix. Therefore good correlation exists between  $^{90}\text{Sr}$  and  $^{154}\text{Eu}$  activity in Chernobyl reactor fuel particles ( $R_{\text{Sr-Eu}}^{\text{FP}} = 72$  for 2000) [7]. This allows estimating *initial*  $^{90}\text{Sr}$  activity inventory within the trench (without account for outside migration):

$$A_{\text{Sr}} = R_{\text{Sr-Eu}}^{\text{FP}} \times A_{\text{Eu}} = 290 \pm 140 \text{ GBq.}$$

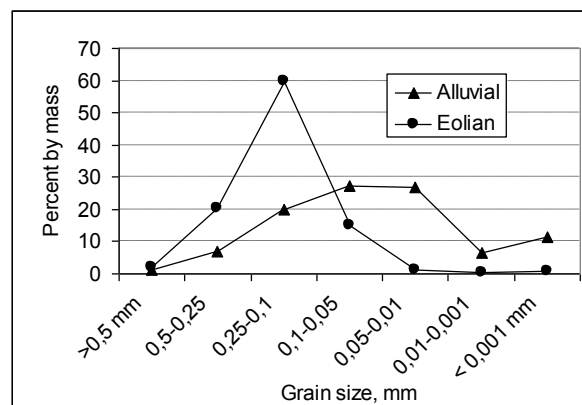
In reality, experimentally determined  $^{90}\text{Sr}/^{154}\text{Eu}$  activity ratio for the trench waste material is  $R_{\text{Sr-Eu}}^{\text{TR}} = 67$  (for 2000), indicating that the trench is on average depleted in  $^{90}\text{Sr}$ . The above data allows us to estimate amount of radiostrontium, which has migrated outside the trench:

$$\Delta S_r = \frac{R_{\text{Sr-Eu}}^{\text{FP}} - R_{\text{Sr-Eu}}^{\text{TR}}}{R_{\text{Sr-Eu}}^{\text{FP}}} 100\% = 7 \pm 5\%.$$

## 4. HYDROGEOLOGY CONTROLS OF RADIONUCLIDE MIGRATION IN GEO-ENVIRONMENT

### 4.1. Geological structure and hydrogeological regime of the site

Geological structure of CPS was characterized from series of 8-9 m deep boreholes, and core material was subjected to grain size analyses. The derived data were compared to characteristic grain size distribution “fingerprints” of the different genetic types of continental sediment facies [4]. As result, the following main packs of sediments of different genetic origin and lithological properties were distinguished within the geologic profile of the CPS (from top to bottom; see Fig.6): artificial “man caused” sediment layer, disturbed by clean-up operations (~114.6-114 m a.s.l.); cover facies of eolian suite (~114-109.5 m a.s.l.); alluvial sediments of the overbank-dead channel facies (109.5-104 m a.s.l.). The characteristic grain-size distribution curves of eolian and alluvial sediments are presented at Fig.4. Eolian sediment pack is relatively homogenous and has low content of clay fraction. On the contrary alluvial sediments have remarkably higher content of fine particles and are rather heterogeneous, representing sequence of sub-horizontal layers of varying grain size composition and thickness. The major sand mineral constituents are quartz (80-90%) and feldspar (10-20%) [5].



**Figure 4.** Grain-size distribution curves for eolian and alluvial sediments.

Hydraulic properties of sediments at CPS were estimated by several alternative techniques including field hydraulic tests (slug and pump-tests on wells), laboratory column experiments, and inverse modeling [4]. From these studies hydraulic conductivity of eolian sands is estimated at  $K_{eol}=3-5$  m/day. The alluvial sediment pack appears to be anisotropic with on average much lower permeability in vertical direction (z):  $K_{al,x}\approx 1$  m/day,  $K_{al,z}\approx 0.02-0.05$  m/day.

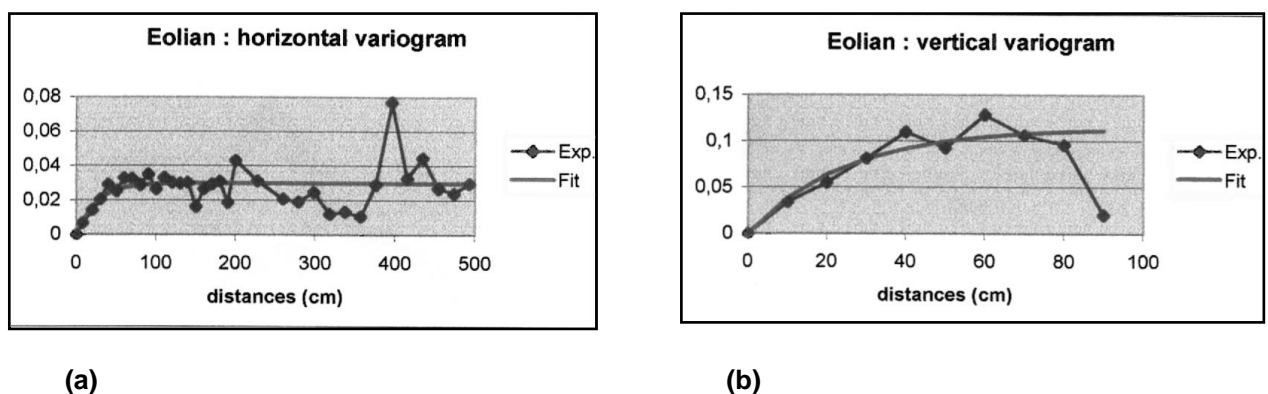
To characterize hydrogeology regime the detailed piezometer network in three dimensions was installed at the CPS (Fig.1, 6). Based on observations of hydraulic head distribution in the aquifer, the flow regime in eolian and alluvial layers appears to be essentially different. In eolian layer the groundwater flows mainly horizontally with average hydraulic head gradient of 0.001-0.002. In lower permeability alluvial sediment pack flow is nearly vertical with by order of magnitude higher head gradient of 0.02-0.04 (Fig.6).

The preliminary indirect estimates of groundwater flow direction and velocity were confirmed in the course of natural gradient tracer test in eolian sand layer conducted at a scale of ~ 1 m using injection of  $^{36}\text{Cl}$  [4]. From this test groundwater flow occurs approximately to the North (see Fig.1), while real groundwater velocity was estimated at ~3 cm/day.

## 4.2. Hydro-dispersion parameters

One of the important focuses of the CPS project is analysis of factors affecting dispersion and attenuation of conservative (e.g.,  $^{36}\text{Cl}$ ) and reactive ( $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$ ) solutes (tracers) in the subsurface environment, and validation of the existing theoretical dispersion models.

In order to get *a priori* estimates of non-sorbing solute hydro-dispersion parameters for the eolian sand layer, geostatistical analysis of spatial distribution of sediment permeability was carried out. The logarithm of mean value of permeability for this layer is 1.61, while the standard deviation is 0.43, which indicates that eolian sediment unit is weakly heterogeneous. The geostatistical analysis of the permeability distribution for the eolian unit leads to the experimental variograms shown at Fig.5.



**Figure 5.** Horizontal and vertical variograms for the permeability of the eolian sediment unit.

In horizontal direction the correlation length for the fitted exponential variogram is  $\Lambda=0.25$  cm and variance is  $\sigma=0.03$ . For the experimental variogram in vertical direction the asymptotic limit (sill) is not reached, indicating that correlation length is larger than the thickness of the formation. The above features of vertical variogram can be related to the stratified micro-structure of eolian sediments.

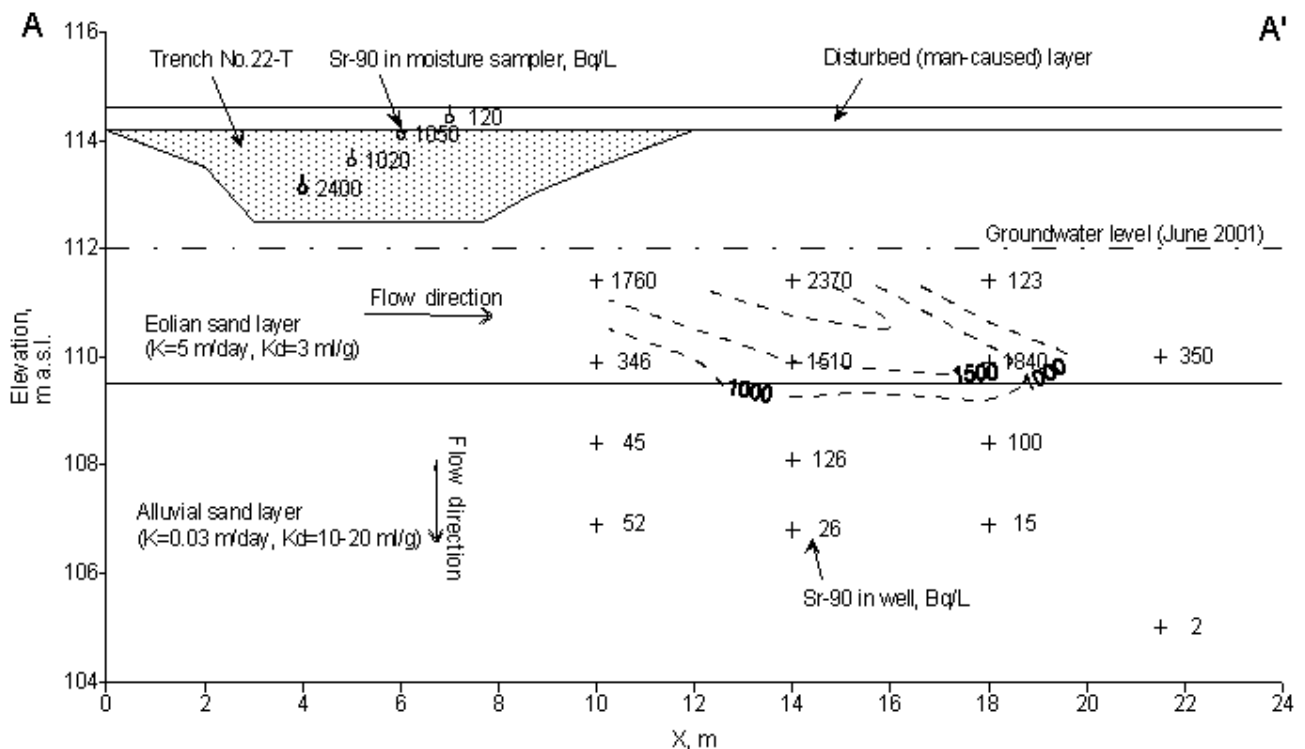
Following the theoretical developments of Dagan [9] the longitudinal dispersivity coefficient related to the horizontal heterogeneity of eolian sediments can be estimated at  $\alpha_L = \Lambda \sigma^2 = 8$  mm. This value can be considered the lower bound for  $\alpha$ , because other factors additionally contribute to the solute dispersion. The upper bound estimate for dispersivity can be derived using theoretical model of Gelhar [10] developed for the horizontally stratified media, which results in  $\alpha_L = \sigma_K^2 / K^2 L = 1.5/25 \cdot 1 \text{ m} = 6$  cm. Here  $K$  and  $\sigma_K^2$  are average value and standard deviation of permeability of eolian sediments respectively, and  $L$  is scale of the tracer experiment. A larger scale tracer test in natural flow conditions started at CPS in August 2001 will serve as an experimental validation test for the presented theoretical estimates.

## 5. MIGRATION OF THE STRONTIUM-90 PLUME IN THE AQUIFER

### 5.1. Strontium-90 distribution and retardation in the aquifer

$^{90}\text{Sr}$  distribution in the subsurface was characterized using series of multilevel wells installed to the aquifer along the groundwater flow direction, as determined from the tracer test. In addition, the ceramic vacuum moisture samplers were installed to unsaturated zone inside the trench (see Fig.6).

The  $^{90}\text{Sr}$  plume in the aquifer with concentrations of  $\sim 1000$ - $2000$  Bq/L (i.e., similar to porous solutions inside the trench) extends from the trench approximately 10 m downstream. Background activity in the top part of the aquifer of an order of  $n \times 100$  Bq/L is due to vertical migration in unsaturated zone from the “man-caused” layer containing residual contamination. In accordance with groundwater flow pattern, radionuclide plume is slightly “dipping” with distance from the trench, being displaced from top by more “clean” infiltration recharge water. The downstream edge of the plume reaches interface zone between eolian and alluvial layers. Here dissolved  $^{90}\text{Sr}$  encounters alluvial sediments with much higher sorption and retardation potential due to large content of clay fraction (see Fig.4).



**Figure 6.**  $^{90}\text{Sr}$  distribution in cross-section of the aquifer at CPS in June 2001 (analytical error 10-20 %).

Assuming that the derived in the course tracer experiment estimate of groundwater flow velocity (i.e.,  $\sim 11$  m/year) is representative in the 14 years retrospective,  $^{90}\text{Sr}$  migration velocity in the eolian layer can be estimated at  $\sim 7\%$  of groundwater velocity, and relevant retardation factor is  $R \approx 14$ . The “back-calculated” from  $R$  strontium sorption distribution coefficient ( $K_d$ ) value for eolian sands is 2.7 ml/g.

In addition to indirect estimations,  $^{90}\text{Sr}$   $K_d$  values were studied in laboratory batch experiments, and in special *in-situ* “water-sediment” radioactivity partition tests. The methodology of batch experiments is described in [11]. Groundwater from CPS was used as a test solution (Table 1). For the purpose of *in-situ*  $K_d$  determinations, sediment cores were extracted from the water saturated top part of eolian layer, and porous solution was immediately separated from matrix by applying vacuum. Next,  $^{90}\text{Sr}$  activity was separately determined for liquid and solid phase, and  $K_d$  values were estimated using straightforward calculations. Results are presented in Table 2. Distribution coefficient values for eolian layer by different methods are in good agreement (~2-3 ml/g). Estimated  $K_d$ -s for alluvial sediments are ~ 10 times higher.

**Table 1.** Chemical composition of groundwater from CPS used as test solution in laboratory batch  $^{90}\text{Sr}$   $K_d$  studies (mg/l).

Ca	K	Mg	Na	Fe	Cl	SO <sub>4</sub>	NO <sub>3</sub>	HCO <sub>3</sub>	TDS	pH
25	8.6	1.2	1.4	0.1	2.5	27.2	61.1	12.2	140	5.85

**Table 2.** Average and range (in parentheses) of  $^{90}\text{Sr}$   $K_d$  values determined by different methods (ml/g).

Genetic sediment type	<i>In-situ</i> plume retardation	Batch experiments	<i>In-situ</i> “water-sediment” $^{90}\text{Sr}$ partition tests
Eolian sands	2.7	2.8	2.0 (0.2-5)
Alluvial sediments	No data	20 (6-50)	No data

## 5.2. Strontium-90 inventory in the aquifer

The data on  $^{90}\text{Sr}$  distribution in groundwater and derived  $K_d$  estimates allow direct evaluating radionuclide inventory in the aquifer. Amount of  $^{90}\text{Sr}$  (both dissolved in groundwater and adsorbed on sediments) was calculated via spatial integration:

$$A_{AQ} = \iint C(x, z) (m + \rho K_d) dx dz,$$

where  $A_{AQ}$  is  $^{90}\text{Sr}$  inventory in the aquifer (Bq per 1 m of trench cross-section),  $C(x, z)$  is  $^{90}\text{Sr}$  concentration in groundwater,  $m$  is sediment porosity,  $\rho$  is sediments density, and  $K_d$  is spatially dependent distribution coefficient. Resulting estimate for cross-section A-A’ (see Fig.1) is:

$$A_{AQ} = 200 - 350 \text{ MBq (per 1 m of cross-section).,}$$

assuming that average  $^{90}\text{Sr}$   $K_d$  value for eolian layer ranges from 2 to 3 ml/g, and for alluvial layer from 10 to 20 ml/g.

Initial inventory of  $^{90}\text{Sr}$  within the trench for the considered cross-section ( $A_{TR,0}$ ) was estimated using data on  $^{137}\text{Cs}$  activity in soil for trench section N21 and fission product activity correlations (see paragraph 3.2). Resulting estimate is (for 2000).

$$A_{TR,0} = 5.5 \pm 2.2 \text{ GBq (per 1 m of cross-section).}$$

Therefore, present day amount of  $^{90}\text{Sr}$  in the aquifer in cross-section is ~ 4 to 6.5 % of the initial  $^{90}\text{Sr}$  inventory in trench. The last value is in good agreement with the presented earlier (paragraph 3.2) independent global estimate of  $^{90}\text{Sr}$  release from trench (i.e.,  $7\pm 5\%$ ) based on comparing  $^{90}\text{Sr}$  to  $^{154}\text{Eu}$  ratio in Chernobyl reactor fuel and in trench material. (Estimate of paragraph 3.2 includes both  $^{90}\text{Sr}$  in the unsaturated zone and in the aquifer). Thus, we get cross-confirmation of radionuclide release from the trench by independent experimental methods.

Lastly, taking into account data of paragraph 3.1 on distribution of radioactivity in source term between different families of fuel particles, it can be concluded that the amount of  $^{90}\text{Sr}$  in the aquifer constitutes ~ 12-23% of initial  $^{90}\text{Sr}$  activity associated in trench with relatively higher solubility U-O fuel particles.

## 6. IMPLICATIONS TO SAFETY ASSESSMENT OF WASTE DUMPS AT CHERNOBYL SITE

The fact that significant portion of radioactivity in fallout in the near zone of ChNPP is associated with relatively stable Zr-U-O particles implies that inventory of activity in waste dumps and soils of Chernobyl NPP site potentially available for geo-migration and biological uptake in dissolved and ion-exchangeable forms should be decreased, while phenomenological waste leaching rate coefficients have to be proportionally increased. On the counter part, some residual contamination will stay in topsoil layer for longer period. Therefore previous risk assessment analyses need to be revised and updated.

Derived site-specific radiological and hydrogeological data and parameters can be immediately used for screening estimation of potential importance of  $^{90}\text{Sr}$  off-site migration from the trench via groundwater pathway. Following [12], we can conservatively estimate downstream "safety distance" ( $L_{saf}$ ) from the trench, beyond which radionuclide concentration in groundwater will be decreased below drinking water standard due to radioactive decay in the course of radionuclide transport in the subsurface as:

$$L_{saf} = \ln \left( \frac{C_0}{C_{dws}} \right) \frac{V}{R\lambda} = \ln \left( \frac{2000}{2} \right) \frac{11}{140.023} m = 236m.$$

Here  $C_0$  is  $^{90}\text{Sr}$  concentration in groundwater below the trench (Bq/L),  $C_{dws}$  is  $^{90}\text{Sr}$  drinking water standard in the Ukraine (2 Bq/L),  $V$  is real groundwater flow velocity (m/y),  $R$  is retardation factor, and  $\lambda$  is  $^{90}\text{Sr}$  decay constant ( $y^{-1}$ ). It is conservatively assumed that groundwater flow is uniform and one-dimensional, and sediments within whole geology cross-section possess minimum sorption capacity.

Results of the above calculation show that  $^{90}\text{Sr}$  spreading from the trench in hazardous concentrations would be limited in future only to first hundreds meters downstream from the waste site. Thus, contrary to some earlier expert judgments (e.g., [13, p.369]) the risk of contamination of Pripjat River located at 2.5 km distance from "Red Forest" site by radioactive groundwater discharge from waste dumps appears to be low. Local geological barriers and hydrogeological settings provide "natural containment" of contaminated groundwater essentially limiting off-site transport of radioactivity to the hydrographic network.

Though *off-site* risks caused by groundwater transport are expected to be low, contaminated ground water is likely to be potential source of significant *on-site* risks, including time scales extending beyond the institutional control period for waste facilities (e.g., 100-300 y). Conceptual understanding, adequate modeling and long-term forecast of radioactive contaminant attenuation mechanisms in subsurface environment are of importance for analysis and planning of waste managing strategy and measures aimed at remediation and rehabilitation of contaminated land and geo-environment at Chernobyl.

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## REFERENCES

- [1] S.P. Dzhepo et al., *Geol.Zhurn.* 1994-4/6 100 (1994) (in Russian).
- [2] *Chernobyl – Ten years on radiological and health impact. An appraisal by the NEA Committee on radiation protection and public health. Reprint*, edited by H. Metivier et al. (OECD, Paris, 1996).
- [3] Y. Saversky et al., *Bulletin of ecological status of the Eclusion zone.* 17, 26 (2001).
- [4] D.A. Bugai et al., in *Water Exchange and Chernobyl Accident*, edited by V. Shestopalov (Ukrainian National Academy of Sciences, Kiev, 2000), p.346 (in Russian).
- [5] D.A. Bugai et al., *Ecological Chemistry*, 14, 273 (1995).
- [6] V.A. Kashparov et al., *Health Phys.*, 76, 251 (1999).
- [7] V.D. Kuriny et al., *Ann.Nucl.Energy*, 20, 415 (1993).
- [8] N. Ahamdach and D. Stammose, *CRAS*, 330, 415 (2000).
- [9] G. Dagan. *Flow and transport in porous formations.* (Springer Verlag, 1989).
- [10] R. Gelhar. *Stochastic subsurface hydrology.* (Prentice Hall, 1993).
- [11] J.R. Patterson and T. Spoel, *Water Resour.Res.*, 17, 513 (1981).
- [12] A.S.Belitsky and E.I.Orlov. *Protection of groundwater from radioactive contamination* (Medicina Publishers, Moscow, 1968) (in Russian).
- [13] *Chernobyl Catastrophe*, edit by V. Baryakhtar (Naukova Dumka Publishers, Kiev, 1995) (in Russian).