

CONF. 9609272--1

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SAN096.2290C

SEP 19 1996

SAND--96-2290C

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**THE CHARACTERIZATION AND RISK ASSESSMENT OF THE "RED FOREST"
RADIOACTIVE WASTE BURIAL SITE AT CHERNOBYL NUCLEAR POWER PLANT**

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Abstract

The "Red Forest" radioactive waste burials created during emergency clean-up activities at Chernobyl Nuclear Power Plant represent a serious source of radioactive contamination of the local ground water system, with ^{90}Sr concentration in ground water exceeding the drinking water standard by 3-4 orders of magnitude. In this paper we present results of our hydrogeological and radiological "Red Forest" site characterization studies, which allow us to estimate ^{90}Sr subsurface migration parameters. We use then these parameters to assess long term radionuclide transport to groundwater and surface water, and to analyze associated health risks. Our analyses indicate that ^{90}Sr transport via ground water pathway from "Red Forest" burials to the adjacent Pripyat River is relatively insignificant due to slow release of ^{90}Sr from the waste burials (less than 1% of inventory per year) and due to long enough ground water residence time in the subsurface, which allows substantial decay of the radioactive contaminant. This result and our previous analyses indicate that though conditions of radioactive waste storage in burials do not satisfy Ukrainian regulation on radiation protection, health risks caused by radionuclide migration to ground water from "Red Forest" burials do not justify application of expensive countermeasures.

Introduction

The "Red Forest" radioactive waste burials were created during emergency clean-up activities at Chernobyl Nuclear Power Plant (Ch.NPP) in 1986-87. The radioactivity contaminated materials (i.e., dead pine "red forest" killed by radiation, soil, litter and debris) were buried *in situ* in shallow (2-3 m deep) unlined trenches. The goals of this hastily planned mitigative measure were to reduce the external exposure rate and to remove the threat of resuspension of radioactivity associated with a fire in the dead "red forest". The inventory of long lived radionuclides disposed at about 1 km² in size "Red Forest" site is estimated at 2160 Ci of ^{90}Sr , 3120 Ci of ^{137}Cs , and 28 Ci of ^{239}Pu and ^{240}Pu . A 1 to 2 m rise of the ground water table occurred in the zone of the burial site from 1987 to 1989, which inundated some burials. An intense radionuclide migration occurred to the local unconfined Quaternary sand aquifer. The primary radioactive contaminant of concern for the groundwater migration is ^{90}Sr . The ^{90}Sr activity in ground water below some burials reached $1.3 \cdot 10^{-6}$ Ci/L in 1989-91, which exceeds the Ukrainian drinking water standard for ^{90}Sr of 100 pCi/L by four orders of magnitude [1,2]. Contaminated groundwater migrates towards Pripyat River, which is tributary to the major Ukrainian water course Dnieper. Also, contamination of the unconfined aquifer threatens water quality in the confined Eocene aquifer underlying Quaternary

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sediments, which is used as a potable water source for Ch.NPP. Therefore, ground water contamination at "Red Forest" site was considered a high priority environmental problem by several authors, and remediation measures have been proposed (e.g., [3]).

In addition, radionuclide migration by biological pathway (i.e., radionuclide transfer to vegetation) occurs from the buried waste. In 1989-91 herb and trees (mainly pines and birches) have been planted at the study area in order to stabilize the soil cover of the waste burials. According to few preliminary sampling data specific activity of the vegetation is about 10^{-6} Ci/kg with respect to ^{90}Sr and ^{137}Cs , and about 10^{-12} - 10^{-11} Ci/kg with respect to ^{239}Pu , ^{240}Pu [4].

Though some preliminary site characterization studies has been conducted at "Red Forest" burials in 1989-91, a number of important hydrogeological and geochemical parameters has not been yet adequately characterized [1]. The major uncertainty is connected with specific chemical form of Chernobyl radioactive contaminants. Radionuclides in the fall-out were associated with fine dispersed reactor fuel (UO_2 matrix) "hot particles". The geochemical mobility of this type of contamination has been a subject of considerable controversy [1,5]. In this paper we present results of our hydrogeological and radiological "Red Forest" site characterization studies, which allow us to estimate *in situ* ^{90}Sr leaching rate from radioactive waste to ground water system as well as other radionuclide subsurface transport parameters. We use then these parameters to assess long term radionuclide transport to ground water and surface water, and to analyze associated health risks.

Site characterization studies

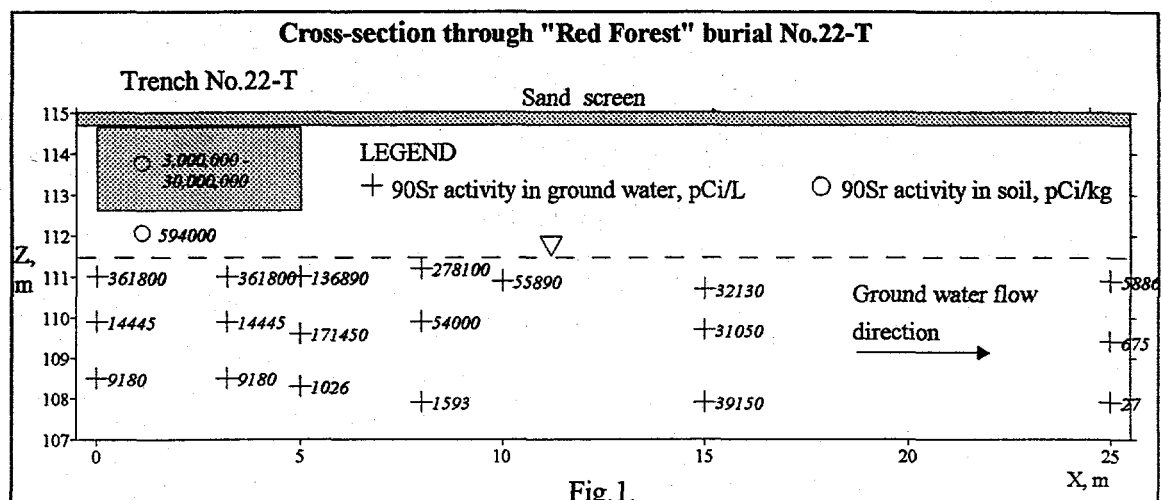
General description of hydrogeological conditions and radioactive contamination at Ch.NPP site is given in [1]. The research program reported in this paper was conducted in 1994-96. It included regional and local scale studies. The regional monitoring well network was installed at the site. From this network the regional hydraulic head gradient in the unconfined aquifer is estimated at 0.003. Combined with hydraulic conductivity estimates of 1-10 m/day and porosity estimate of 0.2 [1], this allows to estimate ground water advection velocity in the unconfined aquifer at 5-55 m/y. Using chlorine ion balance method we derived estimate of ground water recharge of 150-270 mm/y. This range of values is noticeably higher compared to recharge estimates for areas undisturbed by clean-up activities (e.g., 50-60 mm/y [5]). Increase in groundwater recharge may be explained by decrease in evapotranspiration caused by demolition of the forest and removal of top soil layer. This increased recharge probably provoked the rise in groundwater levels at the site in 1987-89.

Major field studies were conducted at the experimental plot located at the "typical" trench burial No.22-T. To determine ^{90}Sr distribution in the subsurface, series of multilevel ground water wells have been installed to the about 20 m thick unconfined aquifer, and soil sampling have been carried out from the trench and underlying vadoze zone (Fig.1). Also, sediment cores were extracted from the aquifer, and ^{90}Sr sorption distribution coefficient (K_d) values in the range from 0.5 to 2 ml/g were estimated based on measurements of radioactivity of pore fluid and sediment matrix. From the radiological sampling data, ^{90}Sr balance in the hydrogeological system was calculated (Table 1). To interpret the data of Table 1, we use a simple first order kinetics source term model, which has been shown in [6] to describe adequately radionuclide leaching from fuel "hot particles":

$$dA_G = K_L A(t) dt,$$

where dA_G is amount of ^{90}Sr leached from a waste burial to vadoze zone and groundwater (Ci), dt is time interval (y), $A(t)$ is amount of ^{90}Sr in burial (Ci) at time t (y), and K_L is leach rate constant

(y^{-1}). From the data of Table 1 we estimate K_L at 0.006 to 0.01 y^{-1} (this corresponds to leach rate of 0.6% to 1% of the total trench ^{90}Sr inventory per year). The above source term model is used later in the ^{90}Sr ground water transport assessment.



Chemical forms of radionuclides in waste samples have been studied using sequential extraction techniques, described in [6]. Results are presented at Fig.2. More than 50% of ^{90}Sr in the trench is still associated with fuel particles, and therefore is geochemically immobile. This finding is consistent with observed rather low radionuclide leaching rate to the groundwater system.

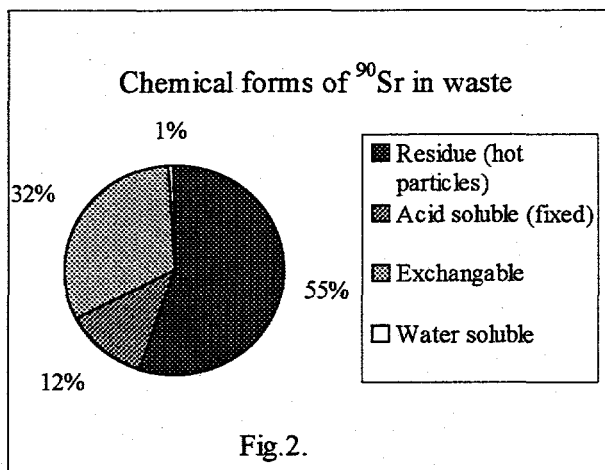


Table 1.
Distribution of ^{90}Sr in the system 'waste burial - vadoze zone - aquifer' at burial No.22-T

Compartment	^{90}Sr inventory, %
Burial	92-95
Vadoze zone	2
Aquifer	3-6

Radionuclide transport and risk assessment

The "Red Forest" site is situated within the 30-km Chernobyl exclusion zone, which serves an institutional control to prevent public from accessing the highly contaminated land. Therefore it is most appropriate to focus radiological risk assessment at populations outside the Chernobyl zone in the downstream Pripyat - Dnieper River basin [3,5].

We have estimated ^{90}Sr transport via ground water pathway from the "Red Forest" burials to the Pripjat River using PAGAN computer code developed at Sandia National Laboratories [7]. We assume that ^{90}Sr leaching rate from all "Red Forest" burials is same as for the trench No.22-T. Hydrogeological and ^{90}Sr subsurface transport parameters have been assigned conservative values based on our field data, e.g. seepage velocity = 55 m/y, $K_d=0.5$ ml/g, $K_L=0.01$ y $^{-1}$. Longitudinal and transverse dispersivities for ^{90}Sr transport in the saturated zone were assigned values 5 m and 0.5 m respectively based on literature data. Estimated ^{90}Sr subsurface flux to the Pripjat River, which is located at the about 2000 m distance down gradient from the "Red Forest" site, is shown at Fig.3. The maximum projected ^{90}Sr transport via ground water to the Pripjat River is about 0.02 Ci/y. This value is insignificant compared to the current off-site ^{90}Sr hydrological transport from the Chernobyl zone, which is governed by direct ^{90}Sr wash-out from the Pripjat River floodplain soils during spring snow melt and rains, e.g. 100 - 355 Ci/y in 1994-95. The health risk caused by current radioactive contamination of water in the Dnieper system are estimated at 10^{-6} - 10^{-7} y $^{-1}$ [3,5]. Thus, ^{90}Sr ground water transport from "Red Forest" burials can only marginally contribute to the hydrological off-site radionuclide transport from Chernobyl site, and associated health risks are far below the level requiring counter-measures.

On-site health risks from radionuclide migration to the unconfined aquifer, assuming that this aquifer is used as a potable water source by a hypothetical self-sufficient resident of the exclusion zone, are analyzed in [4]. It is shown that on-site ground water risk is about two orders of magnitude lesser than health risks due to external and internal exposure (due to consumption of radioactivity contaminated foodstuff) from the surface contamination, and therefore ground water remediation is not "a number one" priority.

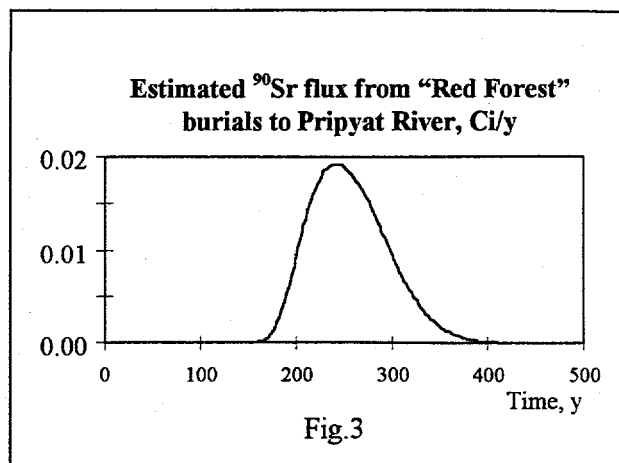


Fig.3

Probability of radioactive contamination of the confined Eocene aquifer and subsequent failure of Ch.NPP water wells is also rather low [8].

Conclusions

Despite generally unfavorable hydrogeology (e.g., high recharge to ground water, low sorption ability of sediments) estimated ^{90}Sr transport from "Red Forest" burials to the Pripjat River is relatively insignificant due to slow release of ^{90}Sr from the waste burials (less than 1% of inventory per year) and due to long enough ground water residence time in the subsurface, which allows substantial decay of radioactive contaminant. More than 50% of ^{90}Sr in the trench is still associated with fuel particles, and therefore is geochemically immobile. Results of this study and our previous analyses [5,8] indicate that, though conditions of radioactive waste storage in burials do not satisfy Ukrainian regulation on radiation protection, health risks caused by radionuclide migration to the ground water from "Red Forest" burials do not justify application of expensive countermeasures. However, besides the ground water pathway, other exposure pathways (e.g., biological radionuclide transport from waste burials) may pose radiological hazard, and research on characterization and risk assessment of "Red Forest" burials should continue.

Acknowledgment

This work was supported by the Ministry on Chernobyl Affairs (Minchernobyl) of the Ukraine. Additional support was provided by the United States National Academy of sciences/National Research Council through the Collaborative Research in Sector Policy Program grant awarded to Dr.R.Waters.

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