Radioecological studies at the Kraton-3 underground nuclear explosion site in 1978–2007: a review

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INTRODUCTION

Four from a total of 81 so-called “peaceful” underground nuclear explosions (PUNE), conducted by the former USSR in the period 1965 to 1988 within the territory of the Russian Federation, were recognized as accidental events and resulted in long-term radioactive contamination of the ecosystems at the sites (Myasnikov et al., 2000). These explosions had code-names: Globus-1, Taiga, Crystal, and Kraton-3. The most dramatic and severe event was the Kraton-3 PUNE conducted near the Polar Circle (65.9°N, 112.3°E) in northwest Yakutia (the Republic of Sakha). Due to technological mistakes and the fact that a borehole mouth was not sufficiently sealed, the explosion resulted in an accidental release of radioactivity (fission and activation products as well as transuranium elements) into the atmosphere. As the site represented a potential long-term source constituting a health hazard for the local human population, complex radiological studies were initiated at the end of the 1980s. At the same time, this site presently serves as an out-door laboratory for continuous studies on the migration of different man-made radionuclides in a variety of environmental media and can, furthermore, lead to improved knowledge with regards to ionizing radiation doses received by non-human biota in Arctic. The area has also been used for practical testing of countermeasures under permafrost conditions. Before 2008, different institutions and organizations conducted more than 25 expeditions to the site itself and to the adjacent areas. Within this paper, some radioecological data and estimates concerning the “Kraton-3” PUNE, that have been published in the available literature sources before August 2007 (including those originally obtained by the authors of this paper), are reviewed.

SOME CHARACTERISTICS OF THE AREA AND EXPLOSION

The area under study belongs to the cool temperature zone (permafrost area). The total amount of annual precipitation is low, falling in the range 250–400 mm. The site is located on the right bank of the Markha River within the North-East Siberian Taiga (boreal forest) with a high predominance (up to 96%) of larch (Larix gmelinii). The area is dominated by sod-carbonate slightly alkaline soil. The PUNE “Kraton-3” was conducted on August 25, 1978 for seismic sounding of the Earth’s crust. The device was detonated at a depth of 577 m, and the energy output was equivalent to about 22 kt of TNT. An unknown proportion of the products of the explosion reached the earth surface shortly after detonation and formed a radioactive plume. The cloud of radioactive debris was dispersed downwind in a northeasterly direction, and twelve minutes after the detonation, the plume passed over the temporary settlement (about 2.5 km from bore-hole) where the participants of the experiment were staying. Despite an urgent evacuation precipitated by extremely high gamma-dose rates in air
(more than 2 Gy per hour), the personnel received up to 300 mSv of acute external irradiation. Contamination of the ground occurred via wet and dry deposition. The initial length of the radioactive trace was reported to be 31 km, and its maximum width was about 1.5 km (Ramzaev et al., 2007a and references therein).

**ALTERATION OF THE FOREST ECOSYSTEM**

In June 1979, it became clear that the trees and some bush species had been killed over an area covering approximately 1 km$^2$ (Miretsky et al., 1997). More than ten years after the explosion (in 1993), mortality effects were reported even for relatively radioresistant lichens (Gedeonov et al., 2002; Ramzaev et al., 2007b) and mosses. The sum of these phenomena observed at the Kraton-3 site is commonly referred to as “dead forest” (Gedeonov et al., 2002). In the beginning of the 2000s, the length of the “dead forest” area was about 3.5 km, and its maximal width was 600 m. A sketch map of the “dead forest” is given in Ramsaev et al. (2007a). Newly formed vegetation cover consists of bush and shrubs plants (*Dasiphora fruticosa*, *Salix*, *Betula*) and microgroups of grasses (*Poa sp*, *Carex*). In 2002, young larch trees of different ages (2–20 years) were found mostly on spots occupied by dead lichens. The seeds and other materials collected from some plants species growing within control and contaminated areas at the Kraton-3 site have been used for morphological and radiobiological studies by several groups of investigators (e.g., Kershengoltz et al., 2002).

**THE CURRENT RADIOACTIVE CONTAMINATION OF THE GROUND**

A description of the initial radionuclide composition of the ground contamination was not found in available literature. The first detailed investigation of the contamination at the Kraton-3 site, including the “dead forest” area, was conducted in 1993 (Gegeonov et al., 2002). A number of man-made radionuclides were found in soil samples: $^{60}$Co, $^{90}$Sr, $^{125}$Sb, $^{134}$Cs, $^{137}$Cs, $^{238}$Pu, $^{239,240}$Pu. Lately, this composition was verified by an independent investigation (Ramzaev et al., 2007c), and traceable amount of $^{152}$Eu, $^{154}$Eu and $^{241}$Am have also been found in soil samples. Presently, $^{137}$Cs strongly dominates (up to 99%) man-made $\gamma$-ray emitting radionuclides. The $^{137}$Cs to $^{90}$Sr ratio in the ground deposit varied widely between sampled plots (0.02–1.64), but the average values, which have been calculated on the data presented by different teams, fall within a very narrow interval: 0.51–0.67 (Ramzaev et al., 2007c). According to the data of Gedeonov et al. (2002), the average $^{137}$Cs to $^{239,240}$Pu activity ratio was equal to 46 in surface soils collected in 1993. A very similar average ratio (a value of 44) for these radionuclides was deduced for soils sampled in 2001–2002 (Ramzaev et al., 2007c). Maximal measured activity concentrations and the estimated ground deposition of radiocaesium, radiostontium and plutonium at the “Kraton-3” site exceed global levels by about four orders of magnitude. The area of the zone with substantial $^{137}$Cs contamination (> 37 kBq m$^{-2}$) was estimated to be about 1 km$^2$ in 2002. Vertical migration of $^{90}$Sr in the undisturbed soil profiles is reported to be more rapid than that for $^{137}$Cs. Nonetheless, the depth of percolation of both radionuclides into the ground is mostly limited to the top 10 cm, which may be explained, primarily, by the presence of permafrost conditions. The horizontal migration of $^{90}$Sr in the aqueous phase exceeded the $^{137}$Cs migration substantially.

**THE CURRENT RADIOACTIVE CONTAMINATION OF THE BIOTA**

Elevated levels of $^{137}$Cs, $^{90}$Sr and $^{239,240}$Pu contents were determined in many samples of live and necrotic biota collected inside the “dead forest” and at the technical area near the Kraton-
3 borehole (Miretsky et al., 1997; Gedeonov et al., 2002; Ramzaev et al., 2007b). The maximal contamination levels: 250, 240 and 7.4 Bq g$^{-1}$ (dry weight) by $^{137}$Cs, $^{90}$Sr and $^{239,240}$Pu, respectively, were reported for the dead epigeic lichens Cladonia. Quite high levels of contamination were found with respect to twigs of dead larches: 14, 44 and 0.09 Bq/g (dry weight) for $^{137}$Cs, $^{90}$Sr and $^{239,240}$Pu, respectively. Caesium-137 transfer aggregated factors ($T_{ag}$s) for lichens, mosses and fungi were 1–2 orders of magnitude greater than those for higher vascular plants, woody species especially. Strontium-90, in contrast to $^{137}$Cs, was distributed more homogeneously in the living compartments of the affected ecosystem. Easily measurable quantities of $^{239,240}$Pu (23 Bq kg$^{-1}$, dry weight) were determined for needles of young larches that had grown after the accident. This may indicate the significance of a root pathway for the secondary contamination of these plants by plutonium.

**EVALUATION OF DOSE RATE AND DOSE**

Gamma-ray dose rate in air has frequently been measured during field studies conducted at the Kraton-3 site (e.g., Miretsky et al., 1997; Kershengoltz et al., 2000; Kovalev, 2002; Ramzaev and Göksu, 2006). Some investigators performed routine dosimetry in tandem with *in situ* γ-ray spectrometry and GPS mapping. The measurements were conducted for several purposes: a) to monitor the radioactive contamination of the area; b) to select an appropriate site for sampling; c) to use the dose rate as a reference value in biological studies; d) to estimate current external γ-ray dose to the critical group of humans. In 2001–2002, the dose rate inside the “dead forest” varied from 70 to 970 nGy h$^{-1}$ (on average 310 nGy h$^{-1}$), which significantly exceeded the background level of about 40–60 nGy h$^{-1}$. It is worth noting that the area of “dead forest” closely corresponded to the area with elevated levels of γ-ray dose rates in air; the spots of dead lichens were found only at the axis of radioactive trace with the maximal dose rates. The cumulative γ-ray doses, attributable to the accident, detected for ceramic materials (porcelain isolators) collected at the “Kraton-3” radioactive trace in 2001–2002 ranged from about 1.2 to 10 Gy; the maximal value was detected for the isolator collected near the Kraton-3 borehole (Ramzaev and Göksu, 2006).

**COUNTERMEASURES**

In 1981, the technical area around the borehole and a part of the contaminated forest were cleaned up. Contaminated topsoil (down to a depth of approximately 20 cm and in selected places 1 m) and vegetation were removed using a bulldozer. The wastes and some equipment were buried in a pit and a trench, excavated at a distance of about 10–15 m to the west of the borehole mouth. The pits and the borehole mouth were covered with “clean” excavated soil. In March–April 2007, the pits and the adjacent territory were additionally covered with five layers (total thickness of about 1.7 m) of a sand-gravel mixture and a layer of geo-textile and geo-membrane. One of the aims of the creation of the multi-layer stone blanket is to keep the content of the repository in constantly frozen (solid) state. Similar technology has been used to construct a banking around the repository site to prevent water and soil erosion.

**KNOWLEDGE GAPS AND FURTHER STUDIES**

Among topics which are waiting further investigations and estimations, the most critical are the evaluations of the total cumulative and current doses to biota from γ-ray, β-ray and α-ray sources. In principle, the current doses to non-human biota could be estimated with the data in hand and existing generic models, while the derivation of cumulative doses would require
additional studies. Detailed analyses of radionuclide bioavailability and continuation of investigations concerning biological effects in plants and, possibly, in small mammals (rodents), as well as the application of ecological risk assessment methodologies could be other topics for study at the Kraton-3 site. Finally, long-term observation of the treated area would give a unique opportunity to obtain new knowledge with respect to the efficiency of countermeasures application under permafrost conditions.

REFERENCES


