IMPACT OF THE RELEASE OF RADIOACTIVE MATERIALS FROM KRASNOYARSK-26 TO THE YENISEI RIVER

Frank L. Parker, Robert D. Waters, Keith L. Compton, Vladimir Novikov

ABSTRACT

During the cold war, production and testing of nuclear weapons in the United States and the Soviet Union led to major releases of radioactive materials to the environment. Although large studies have begun to clarify the magnitude and impact of releases in the United States, only since Perestroika has information become available to begin to evaluate the significance of releases to the environment in the former Soviet Union. This paper reports part of the results of International Institute for Applied System Analysis's Radiation Safety of the Biosphere Project. It deals only with the radiological problems in the Yenisei River downstream of Krasnoyarsk-26 (Mining and Chemical Combine) (Zheleznogorsk). The study, done in collaboration with the site and local administrative authorities, analyzed the impact to the downstream inhabitants of past discharges of radioactive materials to the Yenisei River. A preliminary estimate of the potential doses, based on generic models with site specific information, resulting from the existing contamination was made. Certain areas of the Yenisei River floodplain and island system are significantly contaminated. Conservative estimates of the doses are in the range of 10 mSv per year. However, the potential doses along most of the floodplain are below one mSv per year. Now that the discharge of radioactive materials has been diminished due to the shutdown of two of the three operating reactors and smaller reprocessing loads, the results of the analyses indicate that there does not appear to be a large potential for further contamination downstream of the plant from the relatively limited existing contamination along the flood plains and the islands.

Two hypothetical scenarios were analyzed. The first is the redistribution of existing contamination by a major flood and the doses resulting from such an event. The second scenario is the release of radioactively contaminated sediments from the surface waste storage basins above the banks into the river and an estimate of the resultant doses. The results only give us an insight into the potential consequences of redistribution of presently existing contamination and of the movement of radioactively contaminated sediments from the existing storage basins above the river. During a flood, it appears that the majority of contamination suspended by the higher flows would remain in suspension for long distances resulting in a general pattern of dispersion and leveling out of the contamination along the river. The resulting increases in annual dose are less than tens of microsieverts per year in the Yenisei valley. However, a release from the highly contaminated sediments in the surface storage basins above the river could result in extremely high contamination levels, particularly near the release point. Since accurate data for a hypothetical release were unavailable, the authors assumed unit releases of a relatively small fraction of the contamination in these ponds. Even these limited releases would result in unacceptable levels of contamination and doses. If all of the sediments in the basin were assumed to enter the river due to a hypothetical failure of the berm, containing the wastes, caused by flooding, the computed doses for inhabitants of the floodplains of the Yenisei River could exceed ten millisieverts per year.

It should be noted that discharges to the river are not the not only releases to the environment at this site. Eleven EBequerels (300 million curies) have also been injected underground.

INTRODUCTION

It is now well known that early nuclear weapons development led to large releases of radioactive material to the environment. The United States and the Soviet Union were responsible for the majority of these releases. In the Soviet Union, all such matters were classified as State Secrets. Only since Perestroika, has this veil begun to be lifted. Despite increased interaction with Russian scientists and engineers and the publication of vast amounts of materials there is still a great deal of information not available when trying to determine the present and potential risks at the sites. This is due to many causes. In the earlier days of operation of nuclear sites, alpha and gamma spectrometers did not exist. Everything was subordinated to the military mission and much was still unknown about the human and environmental consequences of exposure to ionizing radiation. Everything was classified as secret, even the existence of such facilities.

Since the end of the "Cold" War, this has changed somewhat. However, although Article 42 of the Russian Federation's Constitution mandates the right to a favorable environment and to reliable information about its condition, much such information is still not available. This may be due, among other things, to security needs, lack of money to declassify documents, and bureaucratic inertia. Particularly lacking are site-specific data on the installations, their contents and their safety. This lack of information has strongly influenced our decision about how to proceed, affecting everything from model choice to the endpoints of the analysis.

At the International Institute for Applied Systems Analysis (IIASA), the Radiation Safety of the Biosphere Project was initiated to study these large releases of radioactive material to the environment. This report deals only with conditions at Krasnoyarsk-26 (1). Because of the sensitive and/or classified nature of some of the data, it was agreed that the study would deal only with offsite effects and that source terms on the site would be aggregated. Thus, individual sources of radioactive material onsite and the safety of their storage were not identified. The results reported in this study only reflect what information was available at the time of the study, and the conclusions are therefore valid only within that limited context. It was also agreed that the Yenisei River would be studied only up to its confluence with the Angara River, 245 km downstream from the site. Though evidence of the releases can be found all the way to the Kara Sea, the major part of the wastes is deposited closer to the plant sites. This distribution of contamination is shown in papers by Bradley and Jenquin (2) and Robinson and Velosov (3). They note that at a distance of 600-800 km downstream of Krasnoyarsk-26 the ^{90}Sr content in floodplain soils is practically at global levels and for ^{137}Cs the distance is even less (The northern hemisphere background levels of ^{137}Cs due to fallout from atmospheric testing are approximately 2 - 2.5 kBq/m^2. The values for ^{90}Sr are approximately 1.5 times less, between 1 - 2 kBq/m^2). Robinson and Velosov (3) report sediment concentrations of 8-27 Bq/kg of ^{137}Cs downstream of the junction of the Angara River with the Yenisei River, 255 km downstream from the discharge site.

Further evidence of low potential doses in the more distant locations is given in the report of the International Arctic Seas Assessment Project (4). There, the maximum annual dose resulting from the best estimate scenario and the plausible worst case scenario to the critical population group, was less than 0.1 and less than 1μSv per year, respectively. This group lives in the Yenisei estuary at the Kara Sea and eat, primarily, locally obtained fish, marine mammals, seabirds and their eggs and spend 250 hours/year on the seashore. The decision to limit the modeling to the nearest major waterway was based upon these low concentrations and estimated doses. In addition to evaluating existing contamination, two other scenarios were evaluated, redistribution of existing contamination by flooding and a hypothetical release of radionuclides from the site into the river system.

The plant, variously known as the Mining and Chemical Combine (MCC), Krasnoyarsk-26 and most recently as Zheleznogorsk was authorized for construction in 1950 to produce plutonium. The site is located on the right bank of the Yenisei River, one of the great Siberian Rivers, approximately 60 km northeast of the city of Krasnoyarsk as shown in Figure 1. The plant covers a territory of about 360 km^2, and occupies 15 km along the right bank of the Yenisei river. The region is characterized by complex relief and divided into a mountainous region and a plains region. The southern part of the Yenisei ridge, where the MCC is located, is representative of typical lowlands with heights up to 600 – 710 m above sea level and depth of river valley cuts up to 300 – 350 m. The climate is sharply continental with a long cold winter, a short dry summer, a late spring, and a rainy autumn.

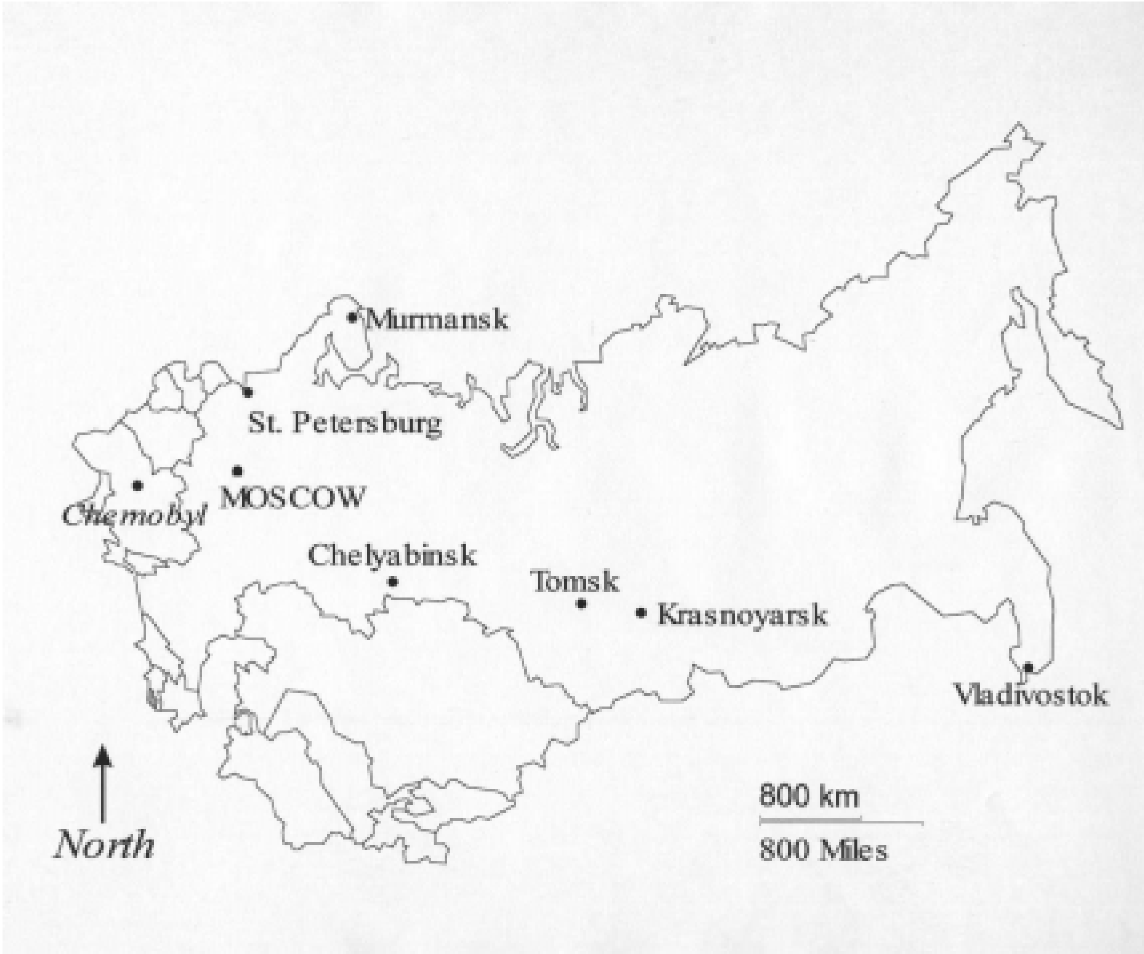


Fig. 1: Map of Russia

The Yenisei River is regulated by the Krasnoyarskaya Hydroelectric Power Plant (HPP) which went into operation in 1967. The HPP is located approximately 85 km upstream of the MCC, and thus reduces the annual fluctuations in river flow in the areas affected by discharges from the MCC. At the city of Krasnoyarsk, approximately 38 km upstream from the MCC, the river is open, not frozen, throughout the year. The average water temperature is $7^{o}C$, current speed is 1.7 m/s, the average depth is 2 m, average width is 1000 m, and the average annual discharge is 2760 m^3/s (5). Typical variations in discharge before and after the dam shown in Figure 1 indicate the dampening of fluctuations in discharge provided by the dam. The Yenisei and its right tributaries (the Shumikha and the Ledyanoy) represent the hydrographic network within the MCC area. The Yenisei is often divided by islets into a number of channels.

The MCC is unique in that the major part of the facility is located underground with the reactors and reprocessing plant in tunnels about 250 to 300 m underground. The MCC consists of 22 different divisions. The main plants are the three plutonium production reactors, the radiochemical reprocessing plant, and the boiler-house. The three reactors and radiochemical plant are located at depths of 250 – 300 m. The MCC is equipped with a ventilation system with filters that serve as barriers to release of radioactive materials to the atmosphere. The first reactor (AD) was decommissioned on June 30, 1992 and the second (ADE-1) on September 29, 1992. The third reactor is still operating and supplies the MCC and Zheleznogorsk with electric power and heat, although since 1990 the power level has been decreased by 20%. This reactor will be used until a fossil fuel (coal) electric plant is constructed in Sosnovoborsk, 10 km south of Zheleznogorsk.

The first two reactors used open loop core cooling. Coolant entered the reactors from the Yenisei River and was discharged back into the river. Therefore, activation products of the water content, corrosion products of the fuel cladding and structural members of the reactor, and fission products from "tramp" uranium and leakage from faulty fuel rods entered the river with the cooling water. These past releases have resulted in radioactive contamination of river water and sediments north (downstream) of the complex. The third reactor, which is still used, has a closed primary cooling cycle. However, the control rods are cooled in a once-through coolant loop and thus represent a potential source of continuing discharge of radioactivity to the Yenisei. The chemical reprocessing complex for plutonium and uranium was commissioned in 1964. Plutonium dioxide and uranium nitrate were produced onsite and then shipped to chemical, metallurgical, and sublimate plants located at other Combines for further reprocessing. With a reduction in plutonium production due to the end of the cold war, operations at the reprocessing plant have been scaled back considerably.

RADIOACTIVE DISCHARGES

Operation of the three reactors and radiochemical plant resulted in large amounts of radioactive waste. The solid radioactive wastes are stored on the MCC territory. The liquid radioactive waste generated as a result of operations have been collected in reservoirs, partly treated, and discharged into the river or pumped into the deep wells. Spray clean up equipment is used so that releases of all radionuclides now varies from 4 to 98 percent of the maximum tolerated releases (MTR). The total amount of beta/gamma radionuclides in waters discharged into the Yenisei in 1993-1994 in GBq/year was 62,000 and 99,000, respectively. The ratio of the 1994 releases to the permissible limits was 0.4. This resulted in mean exposure doses at the water surface in (μR/hr) of 0.9 at V.Dodonovo, 17 km upstream of the discharge point, 15 at 250 m downstream of the discharge point and 10 at 1 km upstream of V.Bolshoi Balchug, ~10 km downstream of the discharge point.

The concentration of ^{90}Sr and ^{137}Cs in the river water are given in Table I.

Table I: Radionuclide concentration in Yenisei River Water (Bq/L)

Distance downstream from discharge point (km)	^{137}Cs	^{90}Sr
99	0.0019	0.0052
177	0.0014	0.0048
245	0.0017	0.0059
278	0.0011	0.0041
803	0.0022	0.0044
1365	0.0019	0.0059

Since the AD and ADE-1 single pass reactors were shutdown, the release of radionuclides into the Yenisei River has been mainly limited to short-lived isotopes (e.g., ^{24}Na,

^{32}P) in the cooling water of the control and protection system of the dual-purpose ADE-2 reactor. Velichkin *et al*. (6) have reported data on effluent activities from the MCC. The activity of the water discharged into the Yenisei River is in the range of 1.2 – 7.0 times the allowable dose concentration for the general population outside the site (the “B category” of the population) (DC_B) for ^{24}Na and 0.05 – 1.5 DC_B for ^{32}P. In recent years the summed release of all radionuclides generally did not exceed permissible levels and was typically within 0.3 – 6.0 % of the maximum permissible release. The volume activity of radionuclides in the river water is below 0.3 DC_B at the discharge location, 0.08 DC_B 500 m from the discharge location downstream, and 0.015 DC_B 15 km downstream from the discharge location (1 km upstream of Bol’shoi Balchug, the first settlement on the right bank of the Yenisei River). The summed values for ^{239}Pu and ^{240}Pu volume activity are lower than the sensitivity limit of the measurement method, and they do not exceed 8.0×10^{-5} DC_B. The maximum values of ^{90}Sr and ^{137}Cs volume activity are 1.2×10^{-3} and 6.0×10^{-3} of DC_B, respectively. The annual effective dose due to the consumption of water from centralized water supply (which draws water from the Yenisei) is estimated to be 5 μSv per year (0.5 millirem per year) at Bolshoi Balchug. After decommissioning of the single-pass reactors the water surface exposure rate and activity of all radionuclides (summed) in the water generally do not exceed the limits set by NRB-76/87 (1988) at the discharge location.

The radioecological conditions in the floodplain of the Yenisei River are mainly due to past reactor coolant discharges from the now-decommissioned single-pass AD and ADE-1 reactors. The exposure rate in most of the inhabited areas of the river bank 15 – 500 km downstream of the MCC discharge location does not exceed 10 – 15 μR/h. However, on particular islands and in some local sections of the floodplain 15 – 250 km downstream of the MCC discharge location there are limited areas with exposure rates of 30 to 200 μR/h (7). In the 300 km-zone downstream of the MCC the radioactive contamination of the floodplain of the Yenisei River is thought to be primarily due to two intense floodings in 1966 and in 1988. The river water discharges were up to 21,000 m^3/s and have led to deposition of suspended bottom sediments containing radionuclides on islands and floodplains (5).

As of January 1, 1996, the area of contaminated lands was 779 hectares. The lands are contaminated primarily with ^{137}Cs and ^{90}Sr radionuclides. The data on the contaminated lands are presented in Table II. More than 5.7 km^2 of the total contaminated land area are at the underground LRW disposal site territory and at the surface basins.

Table II: Contaminated lands at the Mining & Chemical Combine (Egorov, 1998) (Dose rates as measured in the field)

Distribution of the contaminated lands area by the exposure rate level, μR/h	Contaminated lands area, (ha)			
	Total	Including the territories of		
		production zone	Sanitary & protective zone	Observation zone
Total	778.9	330.2	98.7	350
Up to 60	77.7	0.5	66.6	10.6
60 - 120	14.9	-	14.9	-
120 - 240	675.1	329.7	6	339.4
240 - 1000	5		5	
More than 1000	6.2		6.2	

The bottom deposits of the Yenisei downstream of sites of discharge are contaminated mainly with long-lived radionuclides due to the discharges of the previous years.

MCC monitors atmospheric radioactivity at the industrial site, in sanitary-protective zone, and in zone of observation. Fallout of ^{137}Cs from atmosphere in MCC area in 1993 and 1994, respectively, was as follows:

- At the industrial site - 4.8 and 8.1 Bq/m^2-year (1 km north of source of release)
- In sanitary-protective zone - 6.9 and 3.9 Bq/m^2-year
- In zone of observation - 4.2 and 5.0 Bq/m^2-year (8 km north of source of release).

Since decommissioning of the AD and ADE-1 single-pass reactors the activity level in the near-surface layer of the atmosphere has fallen eight fold. In the nearest settlements (the Bol'shoi Balchug village and the town of Zheleznogorsk) in the near-surface layer of the atmosphere, mainly only ^{137}Cs is detected at levels under 0.13 DC_B. On the whole, the effect of gaseous and aerosol effluents of the active production works of the MCC on the contamination of the sanitary & protective zone and of the observation zone is practically indistinguishable from global background levels.

As a result of the MCC operation, large amounts of liquid and solid high, medium, and low-level radioactive wastes have been generated. The solid and liquid radioactive wastes are kept in storage facilities on the MCC territory. The total amount of solid wastes is 130,000 m^3, 105,000 tons and covers 45,000 square meters.

Liquid radioactive wastes resulting from the production operations, depending on their activity level, are sent to cleaning facilities, collected in special tanks or in open storage reservoirs. After treatment and cleaning wastes are sent to underground disposal (at the "Severnyi" site) and decontaminated waters are discharged into the Yenisei River. The total volume of liquid wastes is 5.5 million cubic meters, covering 6.5 million square meters, with 1.1 x 10^{19} Bequerels (300 million curies).

SEDIMENT TRANSPORT AND DOSE CALCULATION METHODOLOGY

The baseline scenario was exposure to radionuclides at present levels and locations in the contaminated river valleys. The doses resulting from this scenario were estimated using two computer codes: RESRAD (8), developed by Argonne National Laboratory; and a beta version of a Russian code, SAMAD, based on the methodology outlined by Georgievskiy (9)

The second scenario was based on a redistribution of radionuclides in the river sediments and floodplain soils due to flooding. The redistribution was calculated for floods varying throughout the range of historically observed discharges. The redistribution of radionuclides was estimated by post-processing the hydraulic output from HEC-RAS (10), a river hydraulics computer code developed by the US Corp of Engineers. The post-processing routines were developed by the project staff to estimate contaminated sediment transport. Redistribution of contaminated sediments was estimated by assuming that the radionuclides were irreversibly sorbed to the sediments and soils in the contaminated reaches. As with the first scenario, the increase in annual dose resulting from this scenario was estimated using the computer codes RESRAD and SAMAD.

The third scenario was based upon a hypothetical release of radionuclides in the liquids and sediments of a holding pond at the site into the river and its sediments. The redistribution of the contaminated sediments was calculated for river discharges of various magnitudes throughout the range of reasonable discharges. The radionuclide inventories associated with these hypothetical releases were based on scenarios that the engineers at TAR site considered feasible. The releases were assumed to enter the river primarily as contaminated sediments via runoff channeled through streams that the sites use to discharge process water. The release and redistribution of radionuclides in the river were modeled using river hydraulic computations from HEC-RAS and sediment transport estimates from in-house post-processing routines. The resulting doses were estimated using RESRAD and SAMAD.

The primary release pathway for ^{137}Cs and ^{90}Sr was probably an accidental release of reprocessing waste from the radiochemical plants. This same pathway is likely the cause of releases of ruthenium, uranium, plutonium and other transuranic radionuclides. The radionuclides ^{60}Co, ^{152}Eu and ^{154}Eu are activated corrosion products that were probably discharged with water used to cool the once-through reactors.

Data related to levels and locations of specific radionuclides were based on site reports and analysis of literature data. The primary measure for reporting contamination data for river bottom sediments and floodplain soil samples was surface contamination density (Ci/km^2). Less frequently, the data were reported in terms of concentrations (e.g., µCi/kg-dry weight of sediment or soil). Typical contamination profiles with depth were reported for the Yenisei River.

Results of aerogamma surveys of the Yenisei River were used to estimate the length of contamination along the river channel. The contamination data for the radionuclides of interest were converted to soil mass concentration values by assuming a mixing depth of 20 cm and a bulk soil density of 1800 kg/m^3.

For scenarios 2 and 3, redistribution of radionuclides was estimated using HEC-RAS to calculate river hydraulic parameters and a post processing routine developed by the project staff to estimate radionuclide transport with sediment. Modeling of redistribution of contaminated sediment proved to be challenging as there are few models capable of modeling of contaminated sediment transport in rivers and deposition on floodplains. This necessitated the development of the original post-processing model described below. The development of original models is, of course, fraught with uncertainty, and the lack of validation requires considerable caution in interpretation of the results of such models.

HEC-RAS was designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. Steady flow water surface profile calculations are currently supported; unsteady flow simulations and sediment transport/movable boundary computations are currently being added to the code. Although the Yenisei River has predominantly sand and gravel bottoms, it was hypothesized that the radionuclides were predominately associated with fine particles (i.e., silt and clay) and only these particle size classes were evaluated.. The underlying theory of fine sediment transport is quite limited in terms of predictive capability; it is governed by empirical relations based on deposition velocities as a function of particle size and critical shear stresses for deposition and scour. The theory used in HEC-6 for fine particle scour and deposition was used in the post-processing routine summarized below. Although limited, this theory is expected to be satisfactory for the scoping-level analyses provided here. Due to lack of site-specific data, the critical shear stresses for scour and deposition were set equal to each other. Therefore, scour was assumed to occur above these critical stresses and deposition is assumed to occur below them.

Releases from the site to the river (Scenario 3) were assumed to be discharged into the overbank when present and into the channel when no overbank is present. The mechanism for the release is not specified. Possible mechanisms for release include

1. Floodwaters washing into the pond and suspending the contaminated pond sediments,
2. A pond failure causing overland flow of water and sediments to the river, or
3. Heavy rains causing overtopping of the pond banks and subsequent overland flow

A unit-exposure approach was used in this study. The estimated doses resulting from unit soil concentrations were scaled to the soil concentrations calculated for each scenario to estimate the doses resulting from these scenarios. Lack of data on variability in lifestyles of the villagers along the river valley precluded a more detailed assessment. The primary assumptions associated with exposure and dose calculations are (1) the amount of time spent on contaminated land, (2) the amount of shielding provided by the house while indoors, (3) the diet consumed by the exposed individuals, and (4) the fraction of the diet grown on contaminated land. The lifestyle of the villagers along the Yenisei River is generally sustenance farming; almost all time is spent on their land and little time is spent away from the village.

The geometry of the Yenisei River in the study area is characterized by a broad floodplain in the region from Atamanovo to Predivinsk (1 to 100 km downstream of the discharge point), followed by a narrowing of the river valley between Predivinsk and Kazachinskoe (100 to 180 km downstream), and a subsequent opening into floodplains from Kazachinskoe down to Strelka (180 to 245 km downstream). The river is dotted with islands throughout the study area. Radiological surveys have indicated that the upstream and downstream ends of islands tend to function as traps for the release of radioactive contamination. This contamination is likely due to hydraulic "dead zones" or low-flow zones due to wake effects of the islands, resulting in increased sediment deposition. The modeling used in this analysis cannot predict deposition based on these processes.

Simplified representations of river channel profiles were provided by technical contacts (11) and compared with those resulting from analysis of a navigation chart of the Yenisei River (12). The slopes of the water surface between each given cross-sectional profile were provided and used to calculate the relative and absolute elevations of the river reaches. These elevations were checked against known gage elevations and found to be in reasonable agreement.

Results of the radiological survey performed in 1990-1991 provided average gamma counts for locations along the left and right banks and on islands in the Yenisei River (5). These data were used to estimate the extent of radionuclide-specific contamination assuming that the radionuclide concentrations associated with the gamma count regions were equal to the sample point data located within the gamma count region. Surface contamination sometimes exceeded one million Bq/m^2 ($30Ci/km^2$) during the 1990 – 1991 timeframe.

The only data collected independently of the MCC is that of Phillips *et al.* (13). These data summarize a joint US/Russian radiological expedition of the Yenisei River in spring and summer of 1995. The three data points on the Yenisei provided by this expedition found that the contamination values were lower but within the same order of magnitude as those of the nearby samples reported by others. The radionuclide concentrations were developed by assuming that the maximum reported concentration in each 1 km stretch of the river is representative of the stretch, whether located on the banks, on an island, or in the sediments. All of the data is decayed from the time of measurement to 1997 to provide a consistent picture of the inventory. For those areas with significant amounts of shorter lived radioactivity, this results in a significant reduction of the initial activity. The total calculated radioactivity of long-lived radionuclides in the floodplains of the Yenisei River valley based on the available data sources is given in Table III. Almost no contamination data were available for ^{90}Sr, because it is a beta emitter and almost all measurements were for gamma emitters. We have assumed that its concentration in floodplain soils is equal to that of ^{137}Cs.

Table III: Estimate of total radioactivity in the floodplains of the Yenisei River from the MCC release point to the confluence with the Angara River.

Radionuclide	Total Radioactivity (GBq)
^{60}Co	170
^{90}Sr	310
^{137}Cs	310
^{152}Eu	290
^{154}Eu	90
Total	1170

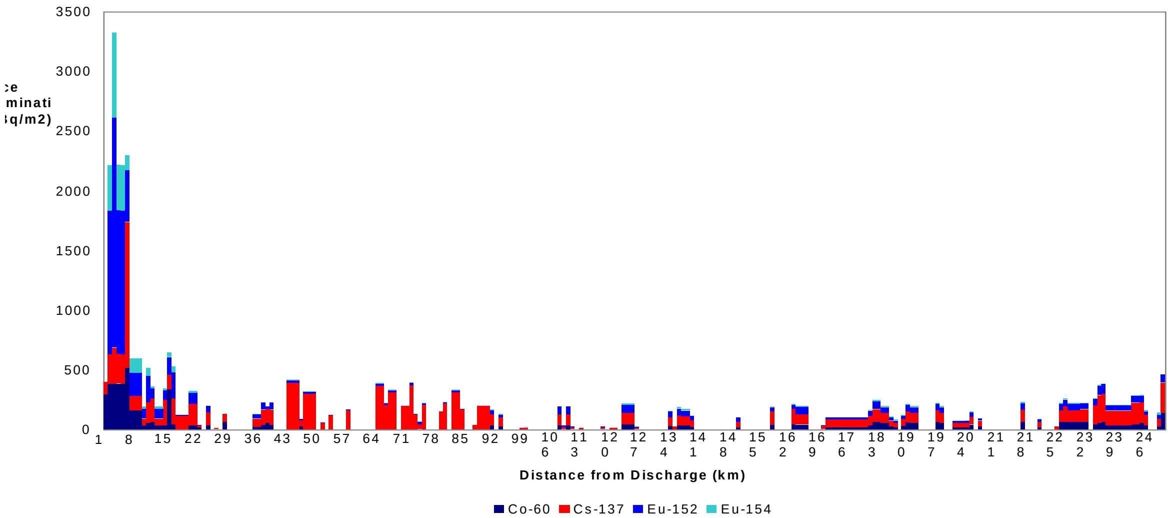
The surface pond that failed and released radionuclides, primarily as sediments to the Yenisei River contained 25,000 to 50, 000 GBq and approximately the same amount of gamma emitting isotopes, primarily ^{137}Cs. The maximum rate of discharge was estimated to equal 525 m^3/s. The duration of discharge at this rate is approximately 6 minutes, which is considerably less than the one-day time step used in the river transport model. Therefore, a one-day pulse release rate is used in the calculations.

RESULTS

Census data are typically considered sensitive in the Russian Federation and no official population data were available for the villages along the Yenisei River. The population in towns and villages along the Yenisei between the release point and the confluence with the Angara River was estimated to be from 12,000 to over 33,000.

Scenario 1 – Existing Contamination Levels and Locations

This scenario is used to evaluate doses due to existing contamination in the Yenisei floodplain. The maximum concentrations of radionuclides are shown for each river kilometer in Figure 2.



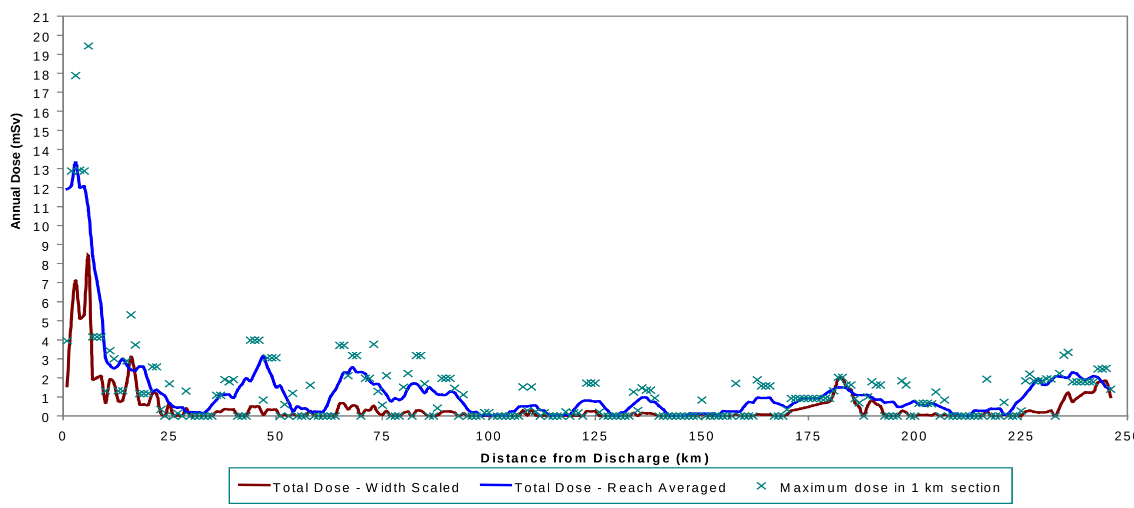


Fig. 2: (a) Maximum 1997 Surface Contamination Values and (b) Dose Estimation

The doses resulting from this distribution are also shown in Figure 2. The individual points represent the sum of the maximum soil contamination values multiplied by the pathway dose conversion factors for each nuclide, and hence represent an absolute maximum of potential individual doses. Because there were no available data for ^{90}Sr contamination, for dose estimation purposes we assumed that its concentration was equal to that of ^{137}Cs.

The average maximum dose along the entire 245 km length of the river is 1.3 mSv, with a standard deviation of 2.35 mSv. If we exclude the peaks located within the first 10 km along the river, the average along the rest of the river is 0.94 mSv, with a standard deviation of 1.12 mSv. Although this technique of simple scaling results in maximum potential doses above the 1 mSv limit along much of the river, many of these points are either isolated spots along the river or are very narrow strips of only a few meters width. Dose averaging may therefore represent a more realistic picture of the potential doses along the river. For most locations along the river, the weighted dose is below the 1 mSv per year (100 mrem per year) Russian permissible dose to the population. The weighted annual dose exceeds the permissible annual limit at locations 1-25 km, 180 - 186 km, and at 235 - 250 km downstream of the release. At the first downstream location, individual nuclides sometimes exceed the annual dose limit by two to three times. At the other points, only the total dose exceeds the dose limit.

The method of longitudinal averaging assumes that the exposed person does not spend all of their time in regions of local contamination maxima. The general picture is quite similar to the previous with the exception that additional peak exposures above the 1 mSv limit also occur from about 37 to 94 km downstream of the discharge point.

Scenario 2 – Redistribution of Existing Contamination By Flooding

This scenario presents an evaluation of doses due to redistribution of existing radioactive contamination by high flows in the Yenisei River. The hydraulic properties of the river channel and overbanks are estimated with HEC-RAS and these properties are used, along with the existing levels and locations of radionuclides in the floodplains, as input to the contamination redistribution routine developed by the project staff. One of the primary calculated hydraulic properties provided by HEC-RAS is the pattern of shear stress in the overbank. The depth and velocity of water flowing in the different segments of the river primarily determines the shear stress pattern. Shear stresses increase with increasing discharges for a given location. The critical shear stress is the stress that determines whether the given conditions result in scour or deposition. The values for the critical shear stresses used in this analysis are 0.7 kg/m^2 for silt and 2. kg/m^2 for clay. At shear values above these values, scour is calculated to occur; below these discharges, deposition is calculated to occur. At a given location along the river, the discharges corresponding to the critical shear stresses can be estimated (e.g., 5700 and 14,200 m^3/s for clay and silt respectively at 32 km from the discharge point).

We expect that redistribution of radionuclides by flooding will result in localized areas of higher concentrations due to ponding in localized depressions along the riverbanks. However, the level of modeling used in this analysis, and the general level of the underlying theory, are not sufficient to make predictions at this level of detail, and the past pattern of deposition will give an indication as to the most significant of these localized deposition zones. The primary concern in this analysis is the potential for widespread contamination of the floodplain which could lead to high collective doses. Except at the lower range of discharges, almost all silt and clay in the channel will remain in the wash load, with subsequent deposition either within the river system further downstream of the study area or in the Kara Sea and Arctic Ocean. At high discharges, the overbank of the Yenisei also has a relatively low trap efficiency for silt (40% or less for discharges at and over 8500 m^3/s. Most of the clay in the overbank is calculated to deposit at 15 – 40 km, 170 – 180 km, and 240 km downstream of the discharge point. The soil particles (and adsorbed radionuclides) washed out of the reach of interest are either subsequently deposited within the Yenisei River system further downstream or discharged into the Kara Sea and Arctic Ocean.

Soil concentrations of ^{137}Cs due to redistribution of existing contamination are shown in Figure 3. Discharges in the range of 5700 m^3/s provide the highest levels of deposition and greatest extent of deposition within the reach of interest.

The maximum average annual dose resulting from the redistribution of existing radionuclides is less than a few tens of μSv per year at 42 km downstream of the release. On average, the doses due to dilution, dispersion, and redistribution of existing radionuclides will be below action levels based on the Russian regulations. Localized spots of higher levels of contamination will likely occur due to specific sediment-trapping characteristics of topography and biota.

Scenario 3 – Release of Radionuclides from Storage Pond

This scenario is concerned with the dose effects of a hypothetical release of radionuclides from the MCC to the Yenisei River. The soil contamination density resulting from a unit release of 37 TBq (1000 Ci) from the surface. Pond to the Yenisei River is shown in Figure 4.

Discharges around 3000 to 10,000 m^3/s provide the most significant redistribution of contamination downstream of the release point within the reach of interest. At these higher flow rates, much of the silt and clay are expected to be retained in the overbanks. The highest levels of contamination are expected to occur at the lowest flows and at locations nearest the discharge point. Contamination densities up to 40 Bq/g may be possible. The densities can be converted directly to dose rate plots as shown in Figure 4. At high flows, the radionuclides are washed downstream. Some deposition will occur at several places downstream in the reach, resulting in dose rates possibly over 10 mSv per year. At low flow rates, an annual dose up to 1 Sv may be expected near the release point. Such dose levels would be the result of essentially complete trapping of contaminated sediments on the floodplain before the release had reached the main channel of the river.

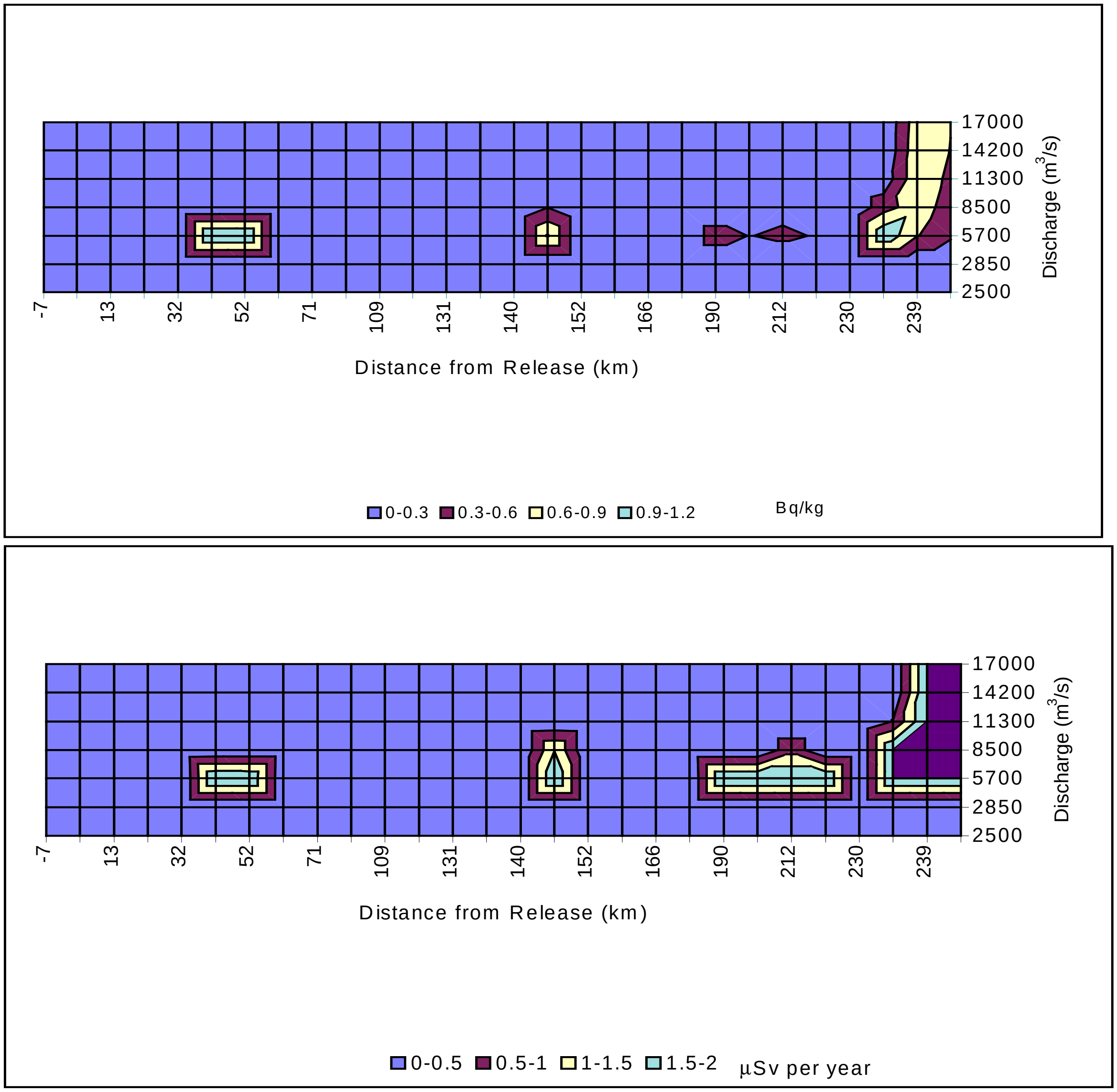
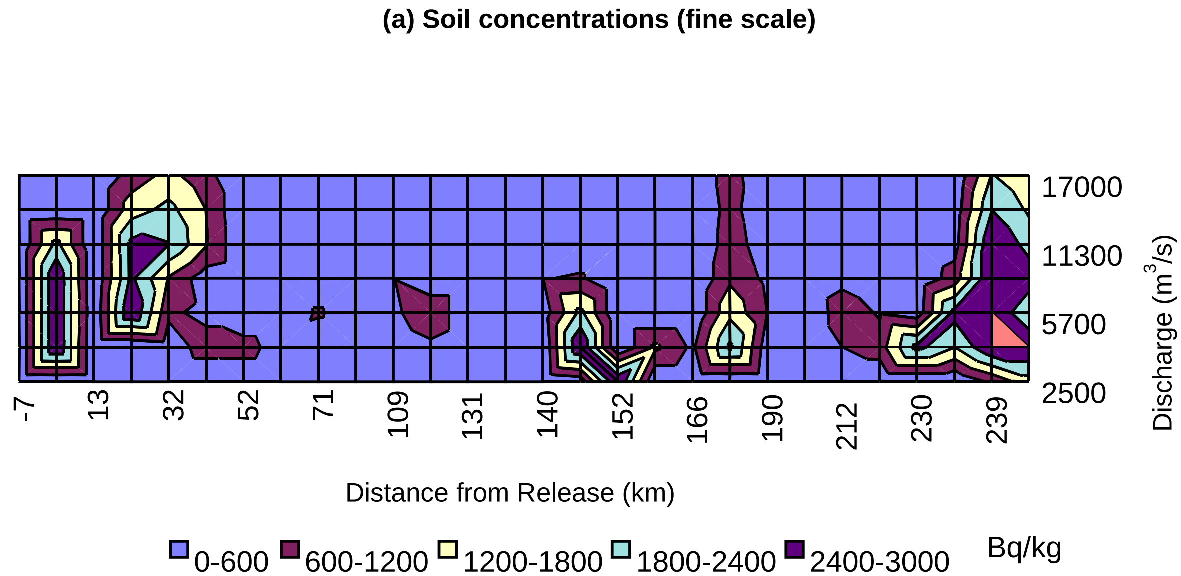


Figure 3: Results of (A) Soil Concentrations of ^{137}Cs and (B) Total Annual Dose from all Radionuclides Based on Redistribution of Existing Contamination in the Yenisei River Floodplains.

The highest doses resulting from a large and sudden release of radioactivity from the site into the river occur when the flows are lowest but still high enough for flow in the overbank. The low flows in the overbank result in significant deposition of contaminated sediments from the pond near the release point.



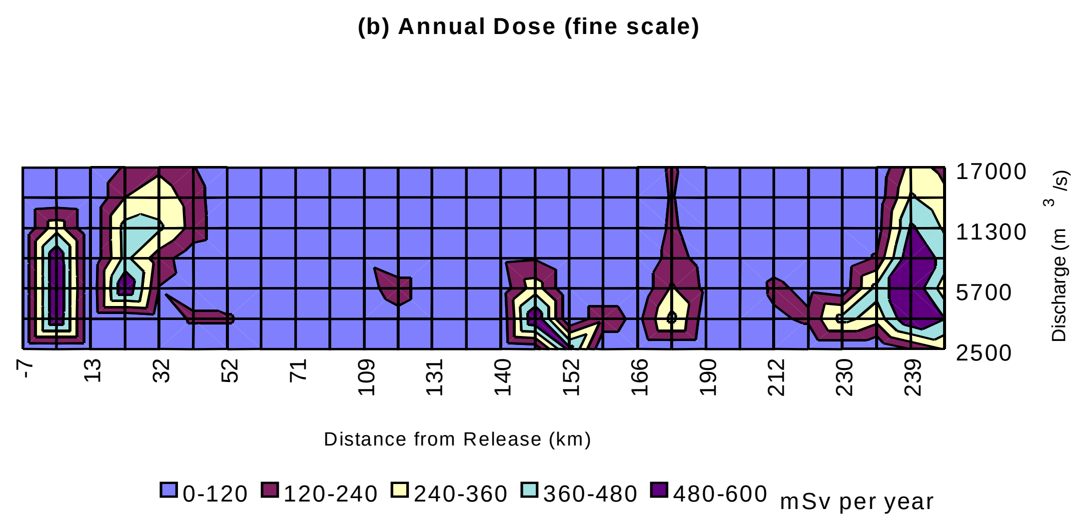


Figure 4: (a) Soil contamination density (Bq/kg) resulting from a unit 37 TBq (1000 Curie) release of radioactivity to the Yenisei River and (b) Total annual dose (Sv per year) resulting from a release of pond no. 365 inventory to the Yenisei River Foundation

CONCLUSIONS

The work to date has provided one of the most comprehensive pictures of the extent and significance of contamination in the Yenisei River valley due to releases from the weapons facilities at Krasnoyarsk-26. In addition, the nature of the problem has dictated the development of original models for estimating the significance of contaminated sediment transport. As with all original work, much remains to be done on model development and validation. However, by basing the development on theoretical principles, these models can assist in scoping the problems posed by contaminated sediment transport in river systems. The work synthesizes all publicly available data relevant to contamination of these river systems. As the modeling has been done on a unit quantity for each isotope of interest, it will be possible to scale the results linearly from the results reported here should new data become available.

The Mining and Chemical Combine (Krasnoyarsk-26) has discharged eta bequerels (millions of curies) directly to the Yenisei River. Despite the release of these sizable amounts of radioactive materials and the high hazard associated with such materials, the environs seem remarkably clean. The concentrations in the sediments of the Yenisei River, decayed to 1997 values, range from less than one to thousands of kBq/m^2. The concentrations of radionuclides in the river water have decreased markedly since the shutdown of the once through water-cooled reactors. These studies have tried to determine the impact of these discharges to the accessible environment (outside the Combine boundary) in the Yenisei River and its flood plains. The impacts from the other releases (e.g., atmospheric, global fallout, accidents, etc.) have not been evaluated, nor has a dose reconstruction of the impact of river water contamination prior to the shutdown of the single pass reactors been conducted.

Evidence of the discharges can be traced all the way to the Arctic Ocean. There are clearly many places along the riverbanks and islands where discharges from the sites have resulted in contamination levels well above natural background levels. However, when the doses to inhabitants near the plants are calculated, they, in many places, turn out to be less than 1 millisievert per year in the Yenisei River valley. In areas within the first 25 km below Krasnoyarsk-26 on the right bank, the calculated dose is greater than 5 millisieverts per year. This dose is based on assumptions of a relatively high degree of occupancy with all their food grown on contaminated lands. At discrete locations downstream, the doses can exceed 1 millisievert per year under conservative exposure assumptions. Although there are areas in the river valley that exhibit significant contamination, it appears that these areas are known to regional authorities and in most places are relatively small or are inaccessible for extended occupation. Future studies focused specifically on the potential exposure of nearby populations in these areas may prove to be of value. In the meantime, access controls are likely to prevent significant doses from being received.

Consumption of contaminated fish may also contribute to the dose. Since the shutdown of the production reactors at Krasnoyarsk-26 with once through cooling, the release of short-lived radionuclides (e.g., ^{24}Na, ^{32}P, and ^{65}Zn) into the river system is mainly determined by discharges of cooling waters of the control rod system of the still operating dual-purpose reactor. It is likely that these releases are responsible for reported fish contamination. Most of this dose is due to short-lived nuclides. If the fish are stored for several days prior to consumption, the dose is reduced by half, primarily due to decay of ^{24}Na. It may be worthwhile to consider technical options to reduce the releases of induced activity or to increase their retention time. It should be noted that fish in this region are also biologically and chemically contaminated, and therefore radioactive contamination is not the only public health concern arising from fish consumption..

When flooding redistributes the existing contamination, the resulting increases in annual dose are less than tens of microsieverts per year in the Yenisei valley. These incremental doses are much less than those due to background radiation. While most of the data on contamination comes from the Combine, there are enough independent studies to indicate that the Combine's assessments of present conditions are reasonably accurate. For the "extreme events", agreed upon by the Combine, all of the sediments, approximately 52 TBq (1400 curies) of gamma emitters with approximately 83% ^{137}Cs and 41 TBq (1100 curies) of beta emitters, were assumed to enter the river due to a hypothetical failure of the berm, caused by flooding. The computed doses for inhabitants of the floodplains of the Yenisei River could exceed ten millisieverts per year. Since there are two ponds on that terrace at the Combine, it seems that if the contents of one of the ponds were washed into the river, then, the contents of the other would also be washed into the river.

The fact that the hydroelectric dam above Krasnoyarsk controls the Yenisei River at and below Krasnoyarsk-26 should not be overlooked. The dam has dampened maximum discharges to half pre-dam maximums and it has significantly dampened variations in flows. Because the dam provides such an important control on the river discharge, contingencies for its use should be evaluated in the event of an accidental release. For example, by lowering the operating level of the reservoir behind the dam, additional storage capacity can be added, which could allow reduced discharges for extended times to allow emergency response to a release. Conversely, the effects of high discharges, which will lower concentrations near the release and flush contamination downstream, should also be evaluated.

The data on which this analysis is based are sparse, given that the areas under study are hundreds of square kilometers in extent. In addition, significant questions remain regarding the quality of the data, and there is a significant lack of extensive independent verification of results reported by the Combine. Based upon these results of this analysis, the question remains: what to do? This is a social, political, economic, and technical decision. It is what Alvin Weinberg calls "transcience", a public policy problem that has scientific underpinnings. Though there are benefits to reducing the doses to as low as possible, the cost, exposure to workers, the absolute reduction in risk to the general public and the disruption in the community must also be taken into account. The decision could be different in each country depending upon its economic situation, competing needs, mores, etc. and even within different parts of the same country. For example in the Clinch River below the Oak Ridge, Tennessee nuclear complex there is radioactive contamination in the flood plain. There is also substantial contamination of the sediments of the river with both hazardous chemicals, primarily mercury, and radioactive material, primarily ^{137}Cs. The major contaminants are a result of releases from two different facilities in the same time frame, 1957-1959. These contaminated sediments are now overlain by less contaminated sediments. The decision has been reached with the concurrence of the local population and the regulatory authorities to leave the sediments undisturbed because their remediation would pose even greater risks than leaving them in place. Of course, monitoring of the situation will continue. This decision, in part, was possible because the local community is technically knowledgeable.

In summary, it appears that despite large releases into the Yenisei River over the past several decades, extensive contamination is not present, and is unlikely to occur unless major releases from liquid waste storage facilities occur. This is due, in part, to the fact that much of the contamination released was short lived and has now decayed to stable isotopes, and, in part, due to hydrological features of the river which allowed only a fraction this activity to be retained in the rivers. The remainder is flushed downstream, deposited along the thousands of kilometers of this large river system and eventually is discharged into the Kara Sea. The high flows of the

Yenisei may have provided sufficient dilution and suspension to prevent large depositions. Of course, contaminated areas exist, particularly in the Yenisei, and may require remediation. It does not appear that remediation of the contamination along the river would pose any intractable engineering problems. It is more likely that selection of a socially, politically, and financially acceptable management plan will pose greater difficulties to the local and regional decision makers.

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In this joint study with our Russian colleagues, we were able to reach agreement on the substance and text of the Conclusions and Recommendations of the study. Different models, philosophic points of view, different methods of handling experimental data would not allow us reach closure on the complete final text.

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