Deep Well Injection of Liquid Radioactive Waste at Krasnoyarsk-26: Volume I

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The work was undertaken jointly by members of the International Institute for Applied Systems Analysis (IIASA) Radiation Safety of the Biosphere Project (RAD Project) and Russian specialists from IGEM, VNIPIPT, and the MCC. Although the main report is being issued by IIASA, the work has been a joint effort. Reports of the individual research groups are available from the RAD Project.

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Executive Summary

Introduction

Early methods of radioactive waste (RW) management in the former Soviet Union (FSU) were plagued with serious problems. At one time, RW was discharged directly to the environment at the Techa River and Karachay Lake, and the practice of storing RWs in tanks led to a tank explosion at Industrial Association (IA) Mayak (also known as the Kyshtym accident) in 1957. These early problems prompted investigations into RW disposal methods that could provide a more reliable isolation of wastes from humans and the accessible environment. Deep well injection was chosen as a potential method of RW disposal, and exploration and investigation of geological structures and materials for the candidate disposal site were performed by the Ministry of Geology. After extensive testing of the concept in the laboratory and the field, and numerous calculations of the likely consequences of deep well injection of radioactive wastes, discharges into deep geological formations at Krasnoyarsk-26 began between 1967 and 1969.

The Mining and Chemical Combine (MCC) at Zheleznogorsk (formerly known as Krasnoyarsk-26) is located along the Yenisei River, approximately 60 km northeast of the city of Krasnoyarsk. The Yenisei River is one of the largest Siberian rivers and runs from south to north in western Siberia. The complex was authorized for construction in 1950 to produce plutonium. The facilities there consist of three plutonium production reactors (two of which were shut down in 1992), a radiochemical reprocessing plant, a reactor water preparation plant, and numerous auxiliary facilities. The MCC is unusual in that all of the major facilities are located 250–300 m underground.

The waste injection site, known as the Northern or "Severny" Site, occupies approximately 6.5 km^2. The disposal site is surrounded by an exclusion zone of 52 km^2, which, at its closest point, lies 1.0–1.5 km from the Yenisei River and roughly parallels the right bank of the river for 7.8 km. The disposal site itself is located approximately 2.5 km from the Yenisei River, 12 km north of the reprocessing plant. It is situated within an ancient erosional depression filled with sand-clay strata reaching 550 m below the ground surface. Interspersed are three aquifers of quartz-feldspar, gravelites, sands, and sandstones. The lower two aquifers, Horizons I and II, at 355–500 m and 180–280 m below ground, are used for injection of intermediate-level waste (ILW)/high-level waste (HLW) and low-level waste (LLW), respectively. Other relevant properties for Horizons I and II include thickness, 55–85 m and 25–45 m, respectively; transmissivity, 5–40 m^2/day and 20–80 m^2/day, respectively; hydraulic conductivity, 0.3–1.6 m/day and 0.1–2.2 m/day, respectively; and groundwater velocity of 5–6 m/yr and 10–15 m/yr, respectively. The recharge areas are believed to be 7 km and 4–5 km to the south. According to Rybalchenko *et al*. (1994), the main discharge area for Horizon I is believed to be the Kan River, 12–14 km to the north. The main discharge area of Horizon II is believed to be the Kan and the Bolshoi Tel Rivers, 4–5 km to the north.

The wastes injected into Horizon I are comprised of 2.25×10^6 m^3 of process wastes, high-level acidic wastes, and medium-level alkaline wastes, and contain a total (decay corrected to 1995) of 9.6×10^{18} becquerels (Bq). The wastes are primarily ^{90}Sr and ^{137}Cs with a specific activity of 5.8×10^9 Bq/L. Almost 3×10^6 m^3 of low-level nonprocess wastes containing 5.6×10^8 Bq have been injected into the lower third of Horizon II, with a specific activity of 2×10^5 Bq/L. This information is taken from the Radleg database.

The injection system for HLW and ILW consists of eight injection wells, eight relief wells, and 54 monitoring and observation wells. HLWs were injected one to two times per year in batches of 1,000–2,000 m^3. ILWs were regularly injected from spring to fall at rates of up to 300 m^3 per day. The increase of pressure in Horizon I due to injection operations is relieved by relief wells located approximately 1 km to the south of the injection array. The LLW system consists of four injection wells, four relief wells, and 37 monitoring wells. The relief wells in Horizon II are not used since the pressure dissipates rapidly. Low-level wastes were injected from spring to fall at rates of up to 600 m^3 per day. Due to the shutdown of the production reactors and the reduced rate of fuel reprocessing, the rate of waste generation has declined considerably in recent years. Wastes are currently injected on an as-required basis. However, the site continues to hold a mining license allowing disposal of all classes of wastes (LLW, ILW, and HLW). The license, which must be renewed every five years, is next due to expire in 2001.

Monitoring results (Table 3, VNIPIPT, 1998) show that the area of the plumes (as defined by nitrates, tritium, and total activity) currently extends over 2 km^2 and 3 km^2 in Horizons I and II, respectively. However, the radioactive component of the plume is expected to occupy a smaller area than the plume defined by nonsorbing constituents. The contours of individual isotopes will differ from the nonsorbing constituent contours due to a variety of reasons, such as radioactive decay and differential sorption of the nuclides by the host formation.

Results

This study was initiated because there were no published, independent assessments of the deep well injection systems at Krasnoyarsk-26 that used site-specific geology and data. Although Foley *et al*. (1996) published an analysis of the entire West Siberian Basin that suggested upwelling groundwater flow in the area of Krasnoyarsk-26, the analysis was of too broad a scale to make a site-specific assessment, and contaminant transport in the region of the disposal site was not evaluated. As a result of problems encountered around the world with chemical deep well injection systems, such as blowouts and seismic shock induction, there was skepticism about the excellent results claimed for the system at Krasnoyarsk-26. The International Institute for Applied Systems Analysis (IIASA), in cooperation with Russian experts, undertook independent analyses of waste migration at the site, using data gathered by Russian official organizations over a 40-year period of exploration and exploitation of the repositories.

Many Russian institutes, such as the All-Russia Design and Research Institute of Production Engineering (VNIPIPT), Gidrospetsgeology, the Russian Academy of Sciences (RAS) Institute of Physical Chemistry, and others, had taken part in the initial assessment on the validity of the concept and implementation of deep well injection. Many continue to work on the problem to this date. A major responsibility has been borne by VNIPIPT, which is part of the Ministry of the Russian Federation for Atomic Energy (Minatom), where the original design of the facility and projections of consequences had been carried out. VNIPIPT was therefore a valuable partner in providing original data and analysis for this study. The Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (IGEM) of the RAS was asked to do an independent assessment for this study by modeling the liquid radioactive waste migration from the MCC disposal site taking into account the effects of thermal and density convection.

To increase the confidence in the results obtained by this study, the problem of contaminant transport was approached through the use of parallel studies. Each of the groups performed an independent analysis of a common data set. This is a common approach in environmental assessment; for example, Rose *et al*. (1993) describe the application of multiple model analysis to the problem of contaminated sediment transport in the Clinch River in Tennessee. The process of modeling teams working independently, then reconciling their results, can lead to increased reliability and insight. There are often many ways to model a system, and many ways to interpret field data. An explicitly parallel study can draw attention to the sensitivity of the results to alternate assumptions, and can increase the confidence in the results when different models yield similar results when similar assumptions are applied. The parallel approach does not necessarily increase the accuracy of the model. Improving the accuracy of the results would require more input data, and a more site-specific model. However, parallel studies provide a way to evaluate the precision of the results. Agreement among parallel modeling efforts is a way of ensuring that key parameters and processes are identified.

Multiple model analysis is, however, more than simply having each team apply separate models (Rose *et al.*, 1993). All of the models must be appropriate to the system under study; the models must be truly different, not simply minor variations of the same code; and agreement must be reached between the modeling groups on the ground rules under which the parallel study will be carried out, to ensure consistency of input data and modeling objectives. For this study, several preparatory meetings between the three major participants (IIASA, VNIPIPT, and IGEM) were held, at which model selection, model scope, and analytical objectives of the analyses were discussed and agreed upon. Some refinement of these original goals occurred as each group prepared their analysis. Members of the parallel study were kept up to date on the activities of the other groups through the preparation of interim reports and by regularly scheduled meetings. The studies produced by the three groups therefore modeled the migration of a generic nonsorbing, nonradioactive tracer, and focused on the area within the boundaries of the site exclusion zone. A common data set was prepared by VNIPIPT, and each group then developed their model independently. The analyses presented here are intended to be conservative screening analyses; there was no attempt in this study to develop a highly detailed, site-specific model.

IIASA undertook several analyses. The first was a simple conservative analysis of the degree of sorption required to prevent waste migration outside the site boundary. The second was a more detailed modeling of contaminated groundwater movement at the site in both Horizons I and II. The final analysis was a conservative analysis of the potential for contamination of the waters of the Bolshoi Tel due to discharges from the injected waste.

VNIPIPT, together with the MCC, coordinated the preparation of input data. Hydrogeological data was prepared based on the material collected by GGP Gidrospetsgeology of the Ministry of Geology. Data on the wastes and their interaction with the repository material was prepared in collaboration with the Institute of Physical Chemistry of the RAS. The VNIPIPT analyses included the distribution of nonsorbed, nonradioactive components of the injected wastes in Horizon I after 1,000 years. Their analysis showed that the maximum concentration at the site boundary after 1,000 years would be 0.001% of the initial injected concentration. The VNIPIPT analysis also included the distribution of nonsorbed, nonradioactive components of the injected wastes in Horizon II after 300 years. The maximum values shown on their plot as reaching the boundary of the site after 300 years was 25% of the initial injected concentration. These results were in accordance with their original predictions. VNIPIPT also performed analysis of the migration of ^{90}Sr in Horizon I and evaluated the effect of density-driven flow in Horizon I.

Scientists at IGEM carried out four studies that focused on the effects of thermal and density convection and on an analysis of the input data provided. The final studies modeled the plume migration in Horizons I and II. Their results showed that the contaminated water moved northeastward, with the denser solutions moving predominantly northward and the less dense solutions moving eastward. Leakage between Aquifers I and II changes the water balance in Aquifer I. The contaminant does not reach the areal boundaries of the exclusion area. Therefore, in the first 1,000 years, the contaminant can escape only through the confining layer. During the 1,000-year period, about 30% of solute mass would escape to the confining layer. The time for travel through the confining layer to Horizon II would then take more than 1,000–2,000 years. The majority of the wastes would have decayed to below regulatory levels during that time period. In Horizon II, wastes migrate to the north-northeast with a velocity of approximately 18 m/yr, with a contact time to the boundary of the exclusion site of approximately 250 years.

The IIASA studies showed that the time for the nonreacting plume from Horizon I to reach the site boundary would take between 1,000 and 1,500 years. Even for this very conservative case, the concentrations in the Bolshoi Tel would still fall within drinking water standards. Although the rate of waste migration in Horizon II is higher, with a nonreacting plume reaching the site boundary within approximately 200 years, the much lower waste concentrations in Horizon II would again result in the concentrations in the Bolshoi Tel being within drinking water standards. The effects of sorption and vertical travel time through the confining clay layer would reduce these already low concentrations in surface waters by several orders of magnitude.

While all models are approximations of real events, VNIPIPT had access to the most complete primary data collected by the Ministry of Geology and to monitoring results collected by the MCC over 30 years. The IGEM and IIASA models had less access to the primary data and no independent data to use. However, the information provided to IGEM and IIASA were based upon the considerably more extensive material available to VNIPIPT, and were considered sufficient to perform the scoping and bounding analyses of this study. Because of the lack of detailed site information and the many simplifying assumptions, the IIASA analyses should be understood for what they are – an attempt to gain insight into conditions at the deep well injection site at Krasnoyarsk-26. The IIASA model should not be considered as a predictive analysis of future conditions.

Conclusions

The three groups made very different assumptions and the degree of confidence they have in the predictive nature of their results also differs. Despite this, the results of the modeling efforts carried out by VNIPIPT, IGEM, and IIASA are similar. There is a remarkable convergence of the results, indicating that the existing system of deep well injection at Krasnoyarsk is functioning as designed. Under the current best understanding of site conditions, there is very little likelihood that the injected wastes would reach the earth’s surface prior to the time that the radioactive materials had been absorbed, decayed, or dispersed to concentrations far below standards set for drinking water.

1

Introduction

The goal of the current study is to make available in the Western literature an independent review of the practice of liquid radioactive waste (LRW) injection into deep wells at the Mining and Chemical Combine (MCC), a nuclear weapons production facility near Krasnoyarsk in western Siberia. Using data provided by the site officials, independent analyses have been conducted by outside organizations (both Russian and international) working together with the in-country experts responsible for waste injection in the Russian Federation. The current report considers only the impact of injection operations under normal conditions. However, work is currently being carried out to evaluate the consequences of both man-made and natural hypothetical failure modes of the repository. The results of the next phase will be made available in a subsequent publication.

Deep well injection of hazardous chemical wastes has been widely practiced around the world for many years (Tsang and Apps, 1996; USEPA, 1990a; USEPA, 1990b). In the United States, it became more prominent in the 1960s when regulation of the discharge of wastes to surface waters became more stringent. From the very beginning, the nuclear industry has been discharging wastes into the ground and deep underground. LRW injection was initiated in the United States nuclear weapons complex in numerous facilities, including the Oak Ridge National Laboratory in Tennessee and the Idaho National Engineering Laboratory.

In the Soviet Union, the severe impacts from the discharge of radioactive wastes (RWs) to the surface waters of the Techa River and Karachay Lake, and the waste tank explosion at Mayak (also known as the Kyshtym accident) in 1957, prompted the specialists in the atomic industry and the Academy of Sciences to seek other options for waste management (Rybalchenko *et al.*, 1994). Geological disposal was one of these options, and it was advocated by Academicians A.P. Vinogradov and V.I. Spitsin, and by Professors S.A. Voznesenskii and N.A. Kalinin. Work started in the latter half of the 1950s to explore the possibilities of disposal at the Siberian Chemical Combine (SCC) located at Tomsk-7 (now known as Seversk), the MCC located at Krasnoyarsk-26 (now known as Zheleznogorsk), the Industrial Association (IA) Mayak located at Chelyabinsk-65 (now known as Ozersk), and the Research Institute of Atomic Reactors (NIIAR) at Dimitrovgrad (see *Figure 1.1*). Exploration and investigation of geological structures and materials for candidate disposal sites was performed by the Ministry of Geology. After extensive testing of the concept in the laboratory and the field, and numerous calculations of the

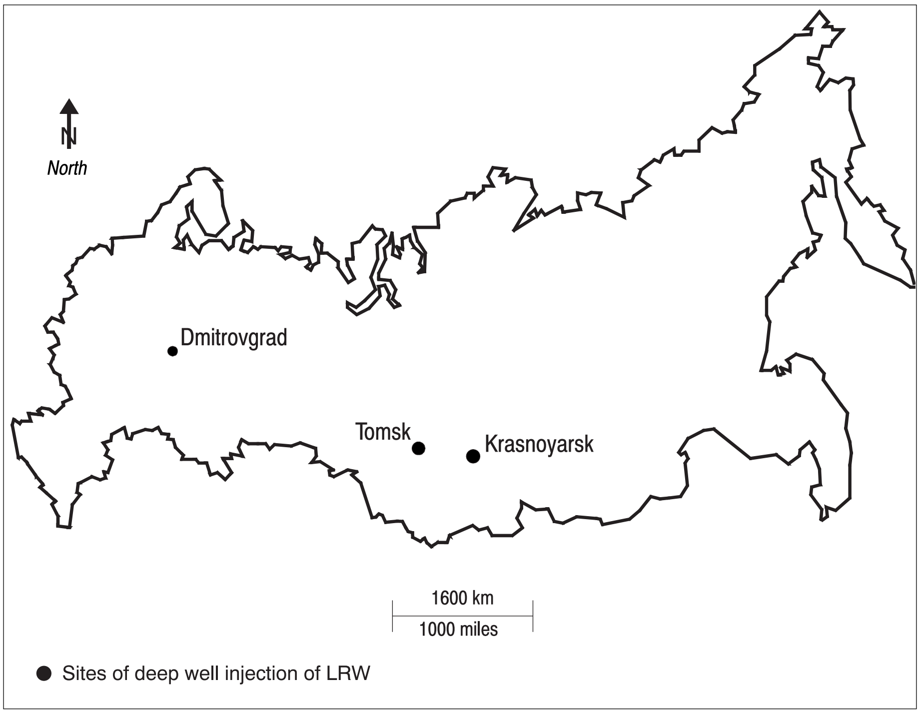

Figure 1.1. Map of major deep well injection facilities in the FSU.

likely consequences of deep well injection of RWs, deep disposal into geologic formations was initiated in the Soviet Union in the early 1960s. Operations began at SCC in 1963, at MCC in 1967–1969, and at NIIAR from 1966–1973. The geology near the Mayak site was judged unsuitable for liquid disposal into deep geologic formations.

In contrast to the United States where studies on deep well injection of RWs were publicly available, in the Soviet Union they were classified until 1976. At that time, generalized discussions on methodology were made available at an International Atomic Energy Agency (IAEA) Conference (Kondratyev *et al.*, 1976). More detailed information about these sites only became available after perestroika with a presentation at the Waste Management 90 conference in Tucson, AZ, USA (Nikipelov *et al.*, 1990). The most detailed information on sites in the former Soviet Union (FSU) became available in 1994 with the publication of *Underground Disposal of Liquid Radioactive Wastes* by Rybalchenko *et al.* (1994). After more than 30 years of operation, the designers and operators of the MCC facility for injection of RWs into deep underground horizons reached the following conclusions:

> "Wastes containing hundreds of millions of curies of radioactive substances have been localized in geologic medium within sanitary protection zones and subsurface exclusion zones. Most of these radioactive nuclides are now in solid phase in the rocks, in the form of sorbed and poorly soluble compounds formed by physical and chemical processes." [Rybalchenko *et al*., 1994]

Disposal of liquid wastes underground in the Russian territory of the FSU is governed by a variety of laws and regulations.[1] Among the most important are "Health Protection Regulations" (SP) and "Technical Conditions for Operating and Closure of Underground Repositories for Liquid Radioactive and Chemical Wastes of Nuclear Fuel Cycle Facilities" (EKCh-93). Disposal is prohibited where it may pollute underground waters that currently are or will be used for water supply, are of major therapeutic value, or that have great industrial significance. The law "on deep geologic formations" that governs the exploitation of such formations was changed and approved by the State Duma on 2 August 1995. The disposal must also be carried out according to the general regulations governing radiation health and safety, as codified in "General Health Protection Requirements for Working with Radioactive Materials and Other Ionizing Radiation Sources" (OSP-72/87). Prime Minister A.N. Kosygin signed the first official documentation concerning underground LRW disposal, No. 3019rs, on 13 September 1958. In 1959 and 1960, a government decree, No. 1036 "On Strengthening State Supervision of the Use of Subsurface Waters and Steps to Protect Them" and a document "Principles on the Procedure for Using and Protecting Subsurface Waters within the USSR," were issued, respectively, which forbid the practice of injection of RWs, except in exceptional cases. A map, "Predictive Map of Hydrogeologic Conditions for the Underground Disposal of Industrial Wastewaters in Deep Aquifer Complexes" was prepared in 1970 and approved by the USSR State Committee on Science and Technology.

In 1979, the "Provisional Sanitary Rules and Specifications for the Construction and Operation of Sites for the Underground Disposal of Liquid Radioactive Wastes" (VSP i TU P3-79) was issued. For 14 years, this document governed the disposal of highly toxic hazardous wastes. Since the formation of the Russian Federation, additional laws have been passed governing the disposal of liquid hazardous wastes underground. They include the "Environmental Protection Act" of 3 March 1992, the "Mineral Resources Act" of 21 February 1992, the "Procedural Rules for Licensing Uses of Mineral Resources" of 15 June 1992, and the "Instructions on Applications of the Procedural Rules for Licensing of Uses of Mineral

[1] The discussion of the Russian legal framework is derived, in the main, from section 4.3 of Rybalchenko *et al*. (1994) and AEA Technology (1997).

Resources." The MCC presented the necessary evidence to comply with existing laws.

The practice of deep well injection has not, however, been without its problems. Accurate prediction of waste migration in the deep subsurface is complicated by complex geochemical phenomena such as partition processes involving acid-base equilibria, adsorption–desorption, precipitation–dissolution, and immiscible-phase separation; and transformation processes such as neutralization, complexation, hydrolysis, oxidation–reduction, catalysis, thermal degradation, and biodegradation (USEPA, 1990b). In addition, there are numerous potential geological problems such as uneven deposition, pinched beds, variable porosities and permeabilities, ill-defined structure due to limited borehole excavation, etc. Early problems associated with gas generation, damage to wellhead equipment, unforeseen migration through undetected abandoned wells, and other issues have led to some skepticism regarding the efficacy of this method of disposal.

Doubts about the the use of deep well injection as a method for RW disposal have been expressed within Russia and in the West. In Russia, this has been due in large part to the limited amount of detailed technical information publically available and the limited independent analysis of the disposal operations. An example of the type and level of skepticism is exemplified by a report of Green Cross of Russia (Robinson and Volosov, 1996). They presented the conclusion of an expert commission on the safety of the operations at the Severny Site which stated, in part:

> • The Severny storage ground is a man-made radioactive deposit presenting high potential ecological hazard.
>
> • The storage ground is not securely isolated from the Yenisei riverbed and the riverbed of its tributary, the Bolshoi Tel River, by the tectonic and lithofacial screens.
>
> • The velocity of the filtrate flow in the northward direction to the middle reaches of the Bolshoi Tel River is 350 m/yr in the second stratum and 250 m/yr in the first.

A more complete extract of the conclusions of the Commission are given in Appendix 3. A response to these conclusions has been prepared by the All-Russia Research and Design Institute of Production Engineering (VNIPIPT) and the MCC, in which specific technical claims given in the quotation from the Green Cross report are rebutted. Their analysis of data gathered over the past 30 years indicate that many of the factual claims quoted in the Green Cross report are inaccurate. Their full response can also be found in Appendix 3.

During the IAEA Seminar "International Cooperation on Nuclear Waste Management in the Russian Federation," skepticism was expressed by the western attendees about the claims for complete safety of the deep well injection systems (IAEA, 1995).

In the United States, skepticism about the approach has arisen because of the problems with Oak Ridge Hydrofracture system and the greater than predicted movement of radionuclides at Hanford, WA, and Idaho Falls, ID. The injection facilities at the Idaho National Engineering Laboratory and at Oak Ridge have been shut down due to technical difficulties and regulatory problems. This skepticism is also reflected in US regulations on deep well injection, which require special exemptions for deep disposal of hazardous wastes.

As a result of this skepticism about the method of deep well injection in general, as reflected in Russian and other laws, there have been a number of efforts to independently examine conditions at the Russian deep well injection sites. The most recent completed study is described in "Measurements, Modeling of Migration, and Possible Radiological Consequences at Deep Well Injection Sites for Liquid Radioactive Wastes in Russia" published as EUR 17626 in 1997 (AEA Technology, 1997). The study dealt mostly with conditions at Dimitrovgrad. The second major study is on the deep well injection system at Tomsk-7 and was conducted by Pacific Northwest National Laboratory (PNNL) of the United States and various Russian research institutes and the SCC. This effort had been halted because of lack of funds but has recently resumed. The third major study, "Evaluation of the Radiological Impact Resulting from the Injection Operations in Tomsk-7 and Krasnoyarsk-26" (prepared by C&E - Consulting and Engineering GmbH and Stoller Ingenieurtechnik GmbH of Germany, Studiecentrum voor Kernenergie - Centre d'Étude de l'Énergie Nucléaire (SCK-CEN) of Belgium, various Russian research institutes, and the MCC) has recently been completed and is being prepared for publication.

In response to the need for additional independent analyses of deep well injection in the FSU, the current study was initiated in the fall of 1997. The work was done by three organizations working under the framework of the Radiation Safety of the Biosphere (RAD) Project of the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. Representatives of the RAD Project inhouse staff at IIASA and of the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (IGEM) of the Russian Academy of Sciences (RAS) worked jointly with experts from VNIPIPT and representatives from the MCC to produce an independent review of site conditions, using data provided by VNIPIPT and the MCC. IIASA and IGEM provided independent analyses of site conditions; the staff of VNIPIPT also produced a new analysis of site conditions.

Over the course of the work, regular meetings were held to review the progress of the analyses and discuss the findings of the research groups. These meetings were also attended by representatives from the Krasnoyarsk regional administration. Data was gathered during regular meetings and during a visit to the injection site itself in the summer of 1998.

There are a number of handicaps that limit the predictive scope of the current study. Lack of time, money, and data have been problems in providing a fully independent and comprehensive analysis of deep well injection at these sites. For example, only in the last decade have any of the details of these formerly secret sites become available. Although it appears that extensive data has been gathered on these sites, much of the basic data on hydrology, geology, and population are not yet publicly available. Some of the data is still regarded as sensitive, some has not been declassified due to cost and time constraints, and some data that could potentially be useful has not been collected. Because these were secret "closed" cities, basic data was often not available even to other Russian institutes. While VNIPIPT had access to the most complete primary data collected by GGP Gidrospetsgeology and monitoring results collected by the MCC over 30 years, IGEM and IIASA had less access to the primary data and no independent data to use. The site-specific data provided could only be checked for internal consistency and agreement with the limited publicly available information on these sites.

These constraints also limited the ability of the IGEM and IIASA teams to construct more sophisticated site-specific models. While all models are approximations of real events, more sophisticated models may better capture the important physical processes. For example, the IIASA analysis does not include the thermal or density effects on waste transport. The IGEM analysis, although it does incorporate these effects, does not account for sorption of the radionuclides to the host rocks. Finally, even IIASA's simple scoping analysis on the effect of sorption does not account for the observed irreversibility of sorption of a fraction of some nuclides observed in Russian studies of the wastes.

Due to these constraints, conservative assumptions were often used where sufficient data were unavailable for a more realistic assessment. Therefore, the scoping analyses of the IIASA and IGEM teams tend to present an artificially high concentration of isotopes in the plumes of the groundwater. A more realistic picture of site conditions would likely yield lower concentrations in groundwater, increased travel times, and a generally more positive picture of repository safety.

In spite of the limited time and data available, important conclusions can be drawn from the analyses conducted in the course of this study. The analyses of IIASA and IGEM should be understood for what they are – an attempt to gain insight into conditions at the deep well injection site at Krasnoyarsk-26. The results presented here should not be considered as a predictive analysis of future conditions. We believe that the value of the current study is that it makes independent analyses publicly available for the first time – though not with independent data – of what could take place in the future under existing conditions. We are already looking at the consequences of hypothetical man-made and natural failure modes of the repository. That will be the subject of a future report.

2
Severny Repository Background[1]

The Severny disposal facility is located approximately 12 km north of the reprocessing plant, on a terrace 100 m above the level of the Yenisei River. The disposal site occupies approximately 6.5 km^2 within an exclusion zone of 52 km^2. The western border of the exclusion zone is 1.0–1.5 km from the right bank of the Yenisei River. The western limit of the disposal area itself is located approximately 2.5 km from the Yenisei River, as shown in *Figure 2.1*.

The area of the injection site is an erosional paleodepression filled with sand-clay strata, reaching a maximum depth of 550 m below ground surface. The natural seismicity of the region is less than six on the 12-point MSK-1964 scale. Stratigraphic columns for the injection site are shown in *Table 2.1*.

The formation is divided into sandy permeable horizons (labeled I, II, and III) separated by clay horizons (labeled B, C, D, and E). Low-permeability deposits of weathered crust (A horizon) underlie Horizon I. Horizons I and II occur in the central part of the site at depths of 370–465 m and 180–280 m, respectively. They are recommended for use as waste disposal strata. These strata are characterized by medium-grained sands and poorly cemented sandstones with the following composition:

Quartz	70–80%
Potassium or sodium feldspars (orthoclase, microcline, plagioclase)	5–15%
Mica and hydromica minerals	∼10%
Clay minerals	3–5%

From the west, the depression is bounded by a fault zone (known as the Pravoberezhny or "Right Bank" Fault), which runs generally north-south, as shown in *Figure 2.1* and *Figure 2.2*. The fault plane is composed of clay, which divides the downthrown (eastern) blocks from the upthrown (western) blocks. The bottom and edges of the depression are formed with gneisses and many-colored overlapping clays. Jurassic formations are represented by interbedding of permeable sand formations and low-permeability clay formations.

[1]Information in this chapter is primarily derived from Rybalchenko *et al*. (1994) unless otherwise noted. Information cited as Robinson and Volosov (1996) reflects data gathered by Green Cross of

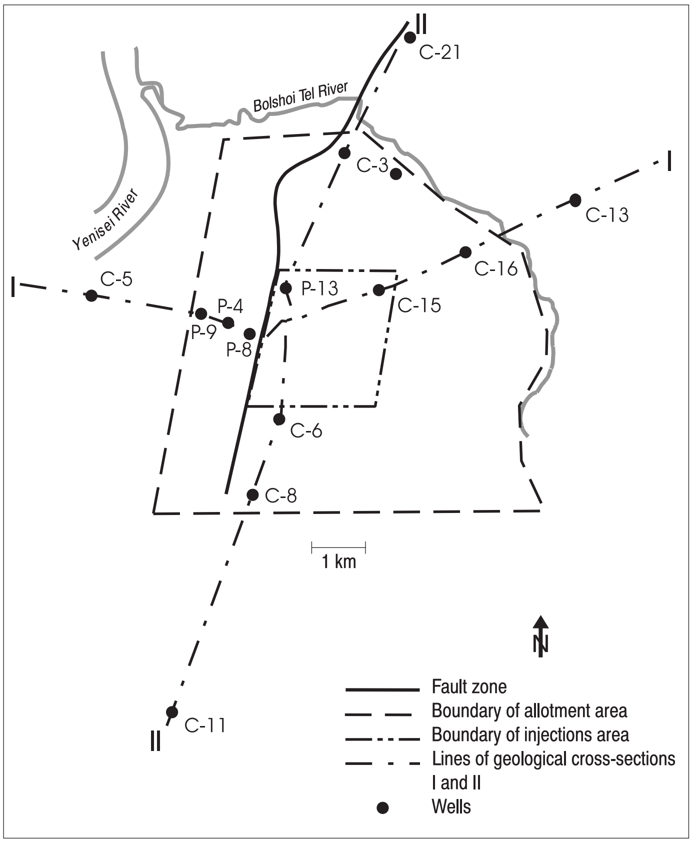

Figure 2.1. Site plan (VNIPIPT, 1998).

The three aquifer horizons at the site are composed of quartz-feldspar gravelites, sands, and sandstones, and are separated by kaolin and hydromicaceous clays and aleurolites, which act as confining layers (Robinson and Volosov, 1996). *Figure 2.2* and *Figure 2.3* show the layers of sand-clay strata that comprise the disposal site.

The deeper Horizon I is used for disposal of intermediate-level waste (ILW) and high-level waste (HLW), and the lower third of Horizon II is used for disposal of low-level waste (LLW). The disposed wastes contain fission products such as strontium, cesium, zirconium, niobium, ruthenium, and cerium, as well as trace amounts of unrecoverable uranium and transuranium elements. Before underground disposal, treatment is carried out at the cleaning facilities of the Mining and Chemical

Russia from official sources and published in a Green Cross summary report on the Krasnoyarsk region.

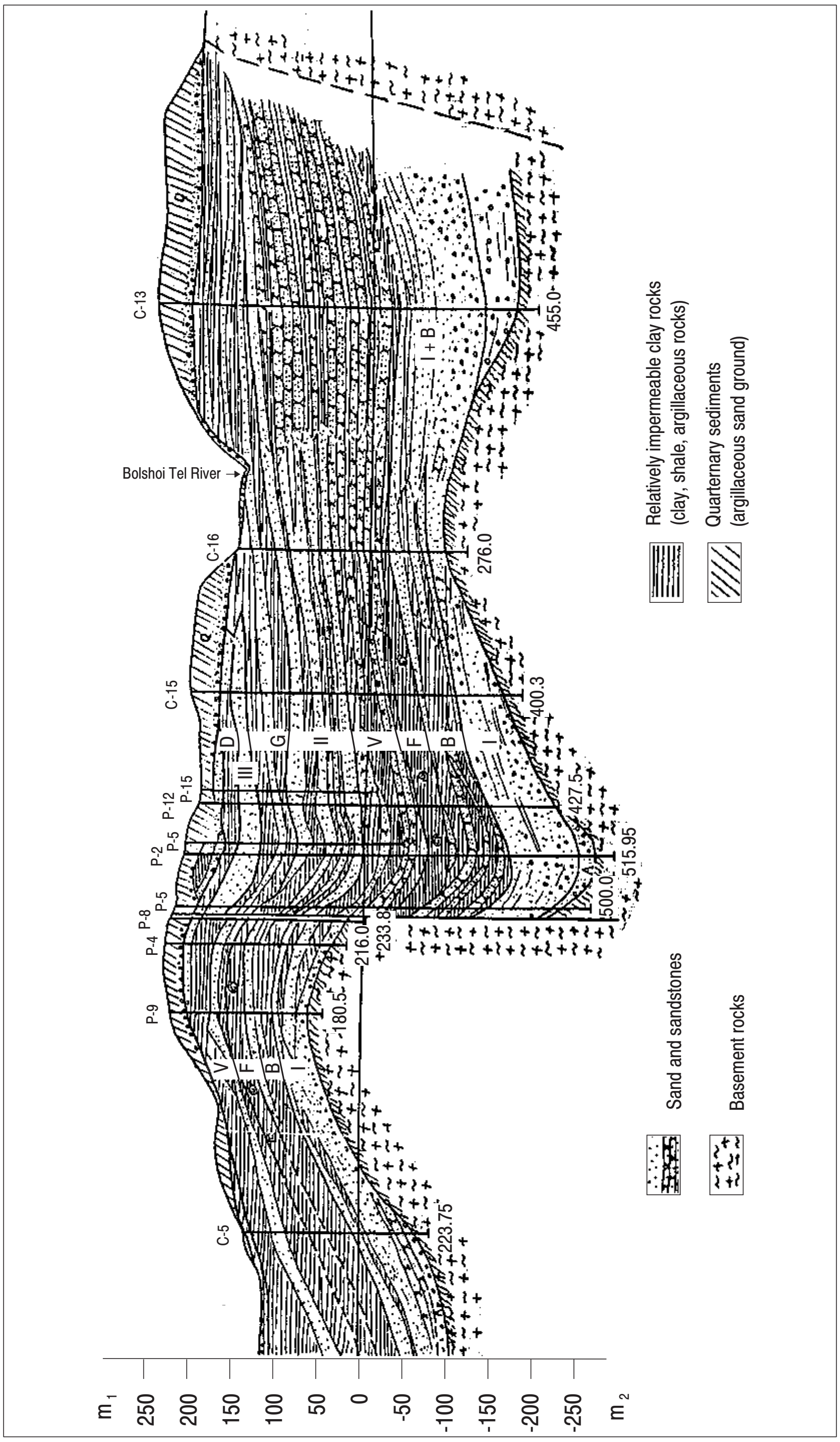

Figure 2.2. East-west cross section along line I (VNIPIPT, 1998).

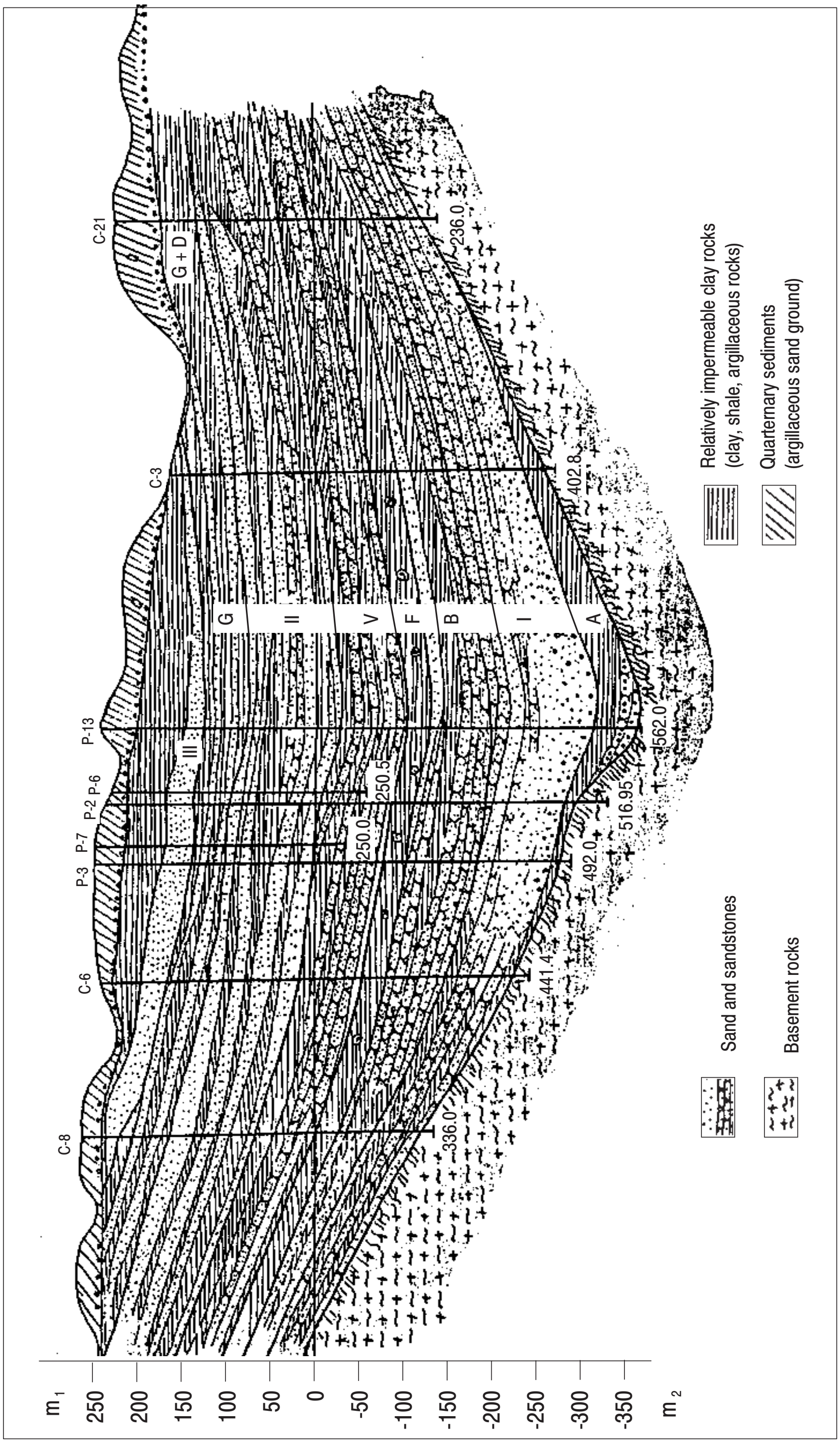

Figure 2.3. North-south cross section along line II (VNIPIPT, 1998).

Table 2.1. Stratigraphic scheme of Paleozoic and Mesosoic-Cenozoic formations in the MCC area.

System	Epoch	Suite	Index	Horizon thickness (m)	Rock description
Jurassic	Middle	Itatskaya	E	20–50	Aleurolite clays
			IIIa	20–50	Aleurolite sands
			E	20–50	Aleurolite argillic clays
			III	0–30	Arkosic sands
			D	30–50	Argillic coal clays
			II	50–95	Aleurites and aleurolites with interbeds of sands and clays
			II	50–95	Carbonaceous clays
			II	50–95	Arkosic sands, sometimes highly carbonaceous with interbeds of clays
			C	45–75	Argillic clays with interbeds of clayey sandstones
			F	0–24	Green argillic clays
			B	30–75	Arkosic sands
	Early	Makarovskaya	B	30–75	Gray argillic clays
			I	0–100	Gravel sands, breccias
			I	0–100	Unsorted wreckage of rocks with limestone cement
Triassic	Late		A	0–43	Many-colored kaoline clays and breccia
Precambrian					Crystalline shales, gneisses

Combine (MCC), and at the radiochemical plant. This treatment ensures compatibility of the wastes with the geological medium, and provides additional recovery of long-lived transuranium elements.

2.1 Geological Studies of the Severny Disposal Site

Special geological prospecting works and explorations preceded the creation of the Severny underground disposal site. These studies were carried out by members of the Krasnoyarsk Territorial Geological Administration from 1959 to 1963, and included a variety of tests. Some idea of the extent of these tests can be seen from the table below:

Seismic prospecting	1,520 km^2
Electrical prospecting	1,520 km^2
Hydrogeologic survey	150 km^2
Test wells, number	77
Test wells, linear meters	35,000
Pumping tests	12
Injection tests	10
Cost (pre-1984 rubles)	3.2 million rubles

These studies were used to substantiate the feasibility of radioactive waste (RW) injection and the safety of disposal. At present, the site holds a mining license which must be renewed every five years, allowing disposal of the wastes. The current license is due to expire in 2001.

Prior to the surveys connected with the identification of a disposal site, only small-scale geologic and geophysical surveys of large areas had been carried out in this region. Geologic prospecting works at the MCC area (Krasnoyarsk-26) specifically were began in 1958 by the Krasnoyarsk Territorial Geological Administration, led by geologists A.V. Goncharov, A.V. Nosukhin, V.T. Ryzhenkov, and others. A special geologic enterprise under the supervision of M.M. Polyakov, governed by PGA Hydrospetsgeologiya, was subsequently organized. Geophysical investigations were carried out under the supervision of G.P. Ponsuy-Shapko and I.T. Gavrilov (Rybalchenko, 1994). As a part of the preliminary research for liquid waste disposal, complex geologic-hydrogeologic surveys and electrical prospecting at 1:100,000 scale were conducted in 1959 at the northern part of the Pravoberezhny site. This work was carried up as far north as the Shumikha River. A report of the work was compiled in 1960 by E.I. Vrublevich, T.Ya. Kornev, A.V. Nosukhin, V.V. Filimonov, and others. In addition, the project research office of the special enterprise headed by M.M. Polyakov conducted engineering geologic investigations in different locations of the Pravoberezhny site over several years. A great quantity of wells, mainly in pre-Jurassic deposits, were drilled along the banks of the Yenisei River, 5 km to the northwest of the village of Novonikolaevka. The area covered was 3×4 km. One deep well (307 m) was drilled in the central part of the site in 1960. The project research office carried out engineering geologic research, accompanied by hand drilling, in 1964 on the area of the projected Severny disposal site. A wide range of drilling and experimental works was conducted by the Enterprise of the Second Hydrogeologic Administration at the Pravoberezhny site in 1960–1963. Results of these works were generalized by A.V. Goncharov, A.V. Nosukhin, and others in a report in 1963. The tectonic structure of the site was described in the context of contemporary ideas regarding its development history and rupture disturbances strike. Seismic prospecting with the aim of tracing the tectonic disturbance revealed by the wells was conducted in 1963 by the Eastern crew of Novosibirsk geophysical trust on a small area of the Pravoberezhny site. However, this problem was not substantially resolved by seismic prospecting.

The work mentioned allowed a characterization of the main features of the geologic composition and hydrogeologic conditions of the Pravoberezhny site. In the course of this work, outlying parts of the site (where recharge and discharge areas of Jurassic aquifers are located) remained poorly understood. Because of this, a complex geologic-hydrogeologic survey at 1:50,000 scale was conducted by A.V. Goncharov, A.V. Nosukhin, and others in 1963–1965. This survey was accompanied by mechanical and hand drilling and by hydrogeologic sampling of wells (Report for 1965). The stratification of Jurassic and Quaternary rocks was conducted by a description of the mapped geologic composition of the territory in accordance with a unified scheme of a West-Siberian depression of Meso-Cenozoic deposits.

More detailed prospecting of a site on the left bank of the Yenisei River was conducted in 1980–1985 in the context of construction of the RT-2 plant, a new radiochemical enterprise at the MCC. Electrical and seismic prospecting and well drilling with a full suite of investigations, including isotopic-geochemical studies, and protracted pumping and injection tests, were conducted (Rybalchenko, 1994). Geologic-geophysical investigations at Yenisei-Kan interfluve territory have been performed in recent years by various organizations for the purposes of evaluating the proposed left bank site for liquid radioactive waste (LRW) disposal and for vitrified HLW disposal site selection. These investigations include work by the Khlopin Radium Institute (monolithic granitoids blocks prospecting), St. Petersburg University (electrical prospecting with audio-magneto-telluric probing), Special Enterprise (SE) Krasnoyarskgeolsemka, and KNIIGIMS (mathematical simulation of geologic sections with the use of gravimetrical data). Research on vertical crustal movements, geologic structure, and geotectonic activity of deep-seated faults at the site from the Krasnoyarsk settlement up to the Kan River mouth were conducted in 1990–1994 by A.P. Lopatin *et al*. (KFGC Priroda) with the use of satellite information. N.V. Lukina is currently researching recent and modern tectonic activity. Research reports can be obtained from these organizations.

2.2 Stratigraphy

The following description is mainly based on the materials of Geologic Composition and Peculiarities of Useful Minerals Location (USSR geologic map of 1:1,000,000 scale), the results of a geologic survey of 1:200,000 scale, and a number of scientific publications. A description is given in the stratigraphic succession shown in *Figure 2.4a*. A map of the most common geologic formations is shown in *Figure 2.4b*. Intrusive formations are included in the appropriate age intervals.

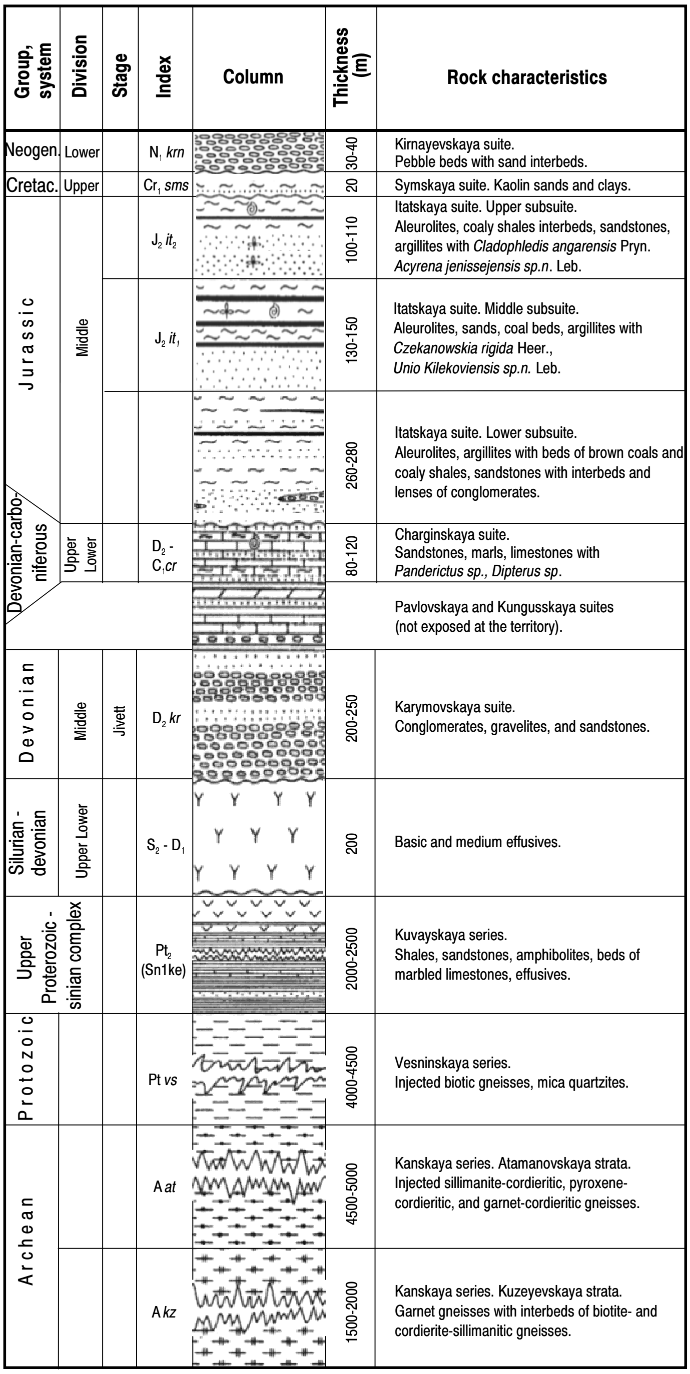

Figure 2.4a. Stratigraphic column for geologic formations of the Yenisei-Kan interfluve area.

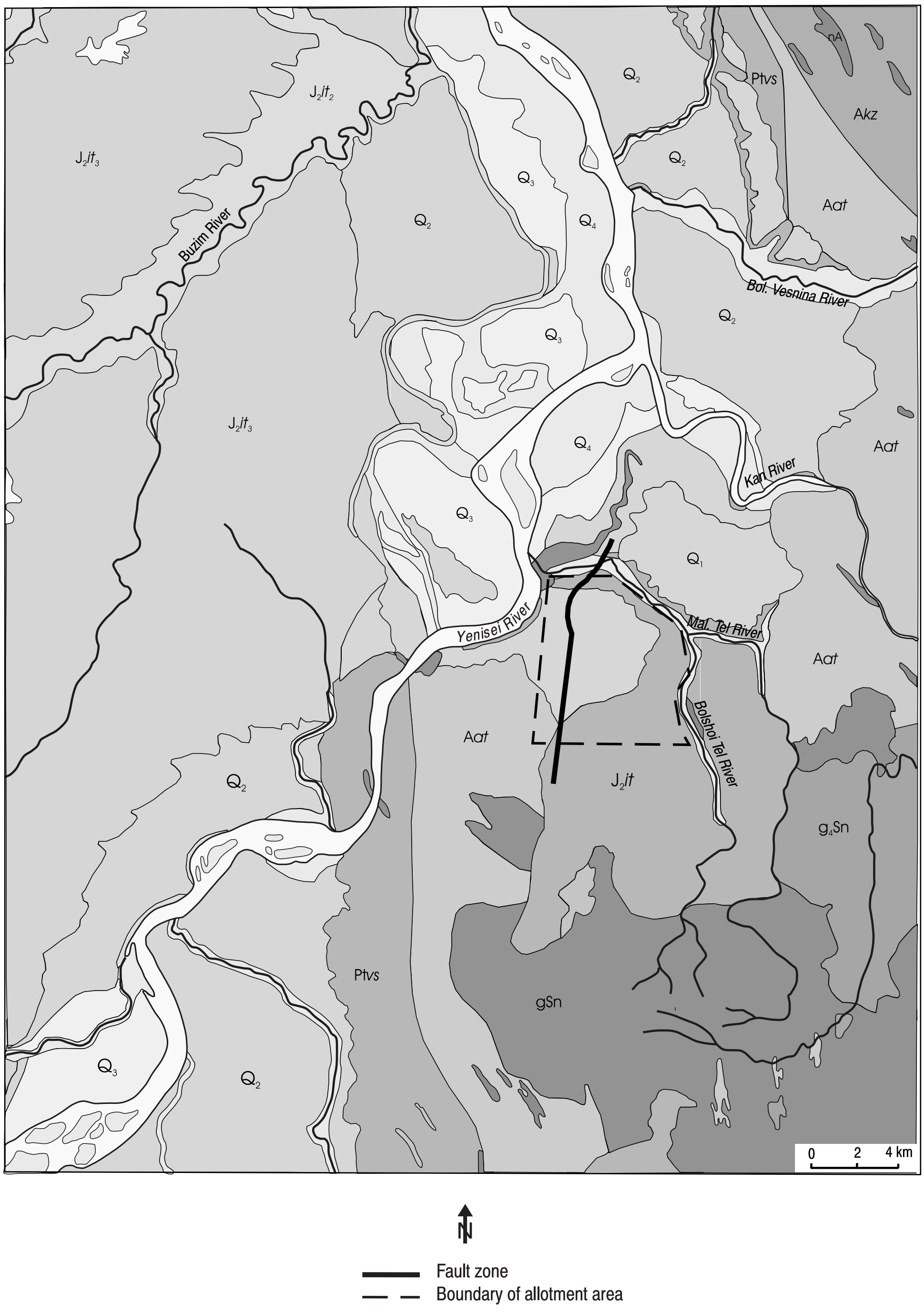

Figure 2.4b. Geological map of the Yenisei-Kan interfluve area. Geological series designations are listed in *Figure 2.4a*, with the exception of Q_1–Q_4 (Quaternary sediments) and gSn (Nizhnekansky granitoids). A full description of these series is given in the text.

2.2.1 Precambrian

The Kanskaya series of the Archean group (the Kansky metamorphic complex) is formed by the rocks of Kuzeyevskaya (Akz) and Atamanovskaya (Aat) strata. The Atamanovskaya stratum, exposed at the right bank of the Yenisei River, extends over the characterized region. Rocks of the Kuzeyevskaya and Atamanovskaya strata belong to granulitic facies of metamorphism. The Atamanovskaya stratum is formed by the rocks characterized by high content of alumina, and is represented by intrusive sillimanite-cordieritic, pyroxene-cordieritic, and garnet-cordieritic gneisses. All mentioned gneiss varieties are linked by gradual transition. Fundamental transformations experienced by these rocks completely changed their initial appearance, and the characteristics of the initial material are open to speculation. The presence of minerals with high alumina content in the rocks of Atamanovskaya and Kuzeyevskaya strata may be evidence that clayey sediments were widespread in the initial material. At the same time, gradual transitions from gabbro and gabbro-norites to pyroxene-plagioclasic rocks reveal that part of the gneisses of the Kanskaya series were formed from primary igneous rocks. The Archean age of the Kanskaya series is established by several factors. Its rocks are broken by Tarakskaya granitic intrusion with an absolute age determined by uranium-thorium-lead methods to be 1,800 million $\pm$ 100 million years. This correlates approximately with early Archean or with the boundary between the early and late Archean.

Rocks of Proterozoic age are represented by the Vesninskaya and Kuvayskaya series and by granitoids of the Nemkinsky and Nizhnekansky complexes. Rocks previously described as the Yeniseisky metamorphic complex are dated to the Vesninskaya series (non–subdivided-PtVs). The extent of this complex includes the right bank of the Yenisei River and the basins of the Kantat, Tertezh, and Temerla Rivers where it forms a wide band, limited from the southwest by granitic intrusion. Rocks forming the Vesninskaya series include micaceous quartzites, intrusive biotitic gneisses, augen gneisses, and amphibolites. Beds of grey-white coarse-crystalline diopsidic marbles are found among biotitic gneisses and schists of Yeniseiskaya series in the northeastern part of the region, in the Maly Vesnina River basin. The total thickness of Vesninskaya series at the section along the Kantat River is approximately 4,000–4,500 m. The Proterozoic age of this series is established by analogy with similar deposits of Eastern Sayan and Eniseisky Ridge in its Transangarsky part.

The Kuvayskaya series (Pt_3(Sn)Kv) was formerly described as the Barkhatovskaya formation. Rocks of the Kuvayskaya series extend over the right bank of the Yenisei River, and over the basins of the Yesaulovka and Temerla Rivers. A section in the bottom of Kuvayskaya series along the Yesaulovka River is comprised of amphibolites, quartz-micaceous schists, and quartz-chloritic schists, and often contains intrusions of rose granites. The thickness of this section is 600–800 m. A layer of schists, limestones, and sandstones approximately 800–900 m thick overlies the the amphibolites and schists. A stratum of volcanogenic rocks, represented by andesitic porphyrites, overlie these areas concordantly, with gradual transition between layers. The thickness of the volcanogenic part of the stratum is 800–900 m. The total thickness of the Kuvayskaya series along the section 2.0–2.5 is several hundred meters. The late Proterozoic age of the series is established by analogy with the Eastern Sayan regions.

Granitoids of the Nemkinsky complex (γ4Sn) extend downstream of the Bolshoi Itat, Nemkina, and Maly Tel Rivers, covering 80–100 km^2. These are represented by grey amphibole-biotitic plagiogranites composed of plagioclase, potassium feldspar, quartz, amphibole and biotite. The chemical composition of these rocks are intermediate between quartz diorites and plagiogranites. Granites of the Nemkinsky complex break deposits of the Vesninskaya series. At the same time, from the bank-sections along the rivers Kan and Bolshoi Itat, it is evident that plagiogranites are forced by the numerous veins and epiphyses of Nizhnekansky granites. The age of Nemkinsky complex has been established as Sinian (Sn).

Granitoids of the Nizhnekansky complex (γSn) are widespread in the basins of the Bolshoi Itat, Bolshoi Tel, and Maly Tel Rivers, where the complex forms a large batholith-type granite massif extending to the northwest. Apart from this massif, small bodies formed by granites of the Nizhnekansky complex are widespread in areas of Precambrian rocks. These linearly extended bodies strike to the northwest, concordant with the strike of the enclosing rocks. Rocks of this complex include biotitic and biotite-muscovitic granites, granite gneisses, and quartz-syenites. Granites of the Nizhnekansky complex are responsible for intense intrusive metamorphism of surrounding rocks. The lower bound on the age of the Nizhnekansky intrusive complex is dated by the fact that granites of this complex break deposits of Kuvayskaya series which are dated to Proterozoic age. The upper bound on the age of the complex is Cambrian, as granites of this type do not break the Cambrian deposits extending over the investigated region. On the basis of present knowledge, the Nizhnekansky granitic complex age may be considered as Later Sinian.

2.2.2 Paleozoic group

Paleozoic formations have a modest areal extent in the southern part of the territory. They include effusives of basic-medium composition of Silurian-Devonian age, terrigenous rocks from conglomerates up to sandstones of Karymovskaya series of Middle-Devonian age (based on plant fossil remains), and sandstone-marl-limestone deposits characterized by fauna of the Devonian-Carboniferous age. The total thickness of Paleozoic deposits is about 500–600 m.

2.2.3 Mesozoic group

Jurassic System

Lower Jurassic sediments do not outcrop in the area and are therefore not reflected in the stratigraphic column shown in *Figure 2.4a*, which was based on the 1:200,000 scale geologic survey. Information of these rocks was obtained as a result of drilling connected with underground LRW disposal (Rybalchenko, 1994). Therefore, all sections of Jurassic deposits in the region of MCC Severny are divided into horizons based upon hydrogeological properties of the rocks and by analogy with sections of Meso-Cenozoic deposits of the SCC (Tomsk-7) injection site. Indexes of Roman numerals indicate aquifer horizons and letters are used to identify aquitards. Horizon boundaries and stratigraphic boundaries in the lower part of the Jurassic section in the region of injection site Severny do not coincide. Variegated kaolinic clays and conglomerates of calcic cement are penetrated by wells in the deepest parts of crystalline basement in the foot of Jurassic sediments. These rocks are considered to be products of redeposition of Triassic-Jurassic weathering crust and are included in the composition of the lower subsuite of the lower-Jurassic Makarovskaya suite. The thickness of these deposits ranges between 0–43 m.

The Makarovskaya suite (J_1mk) comprises, from bottom to top, variegated deposits overlain by ungraded rock fragments with limestone cement, then gristone sands, breccias, and grey argillite-like clays. These deposits then merge with arkosic sands of the middle Jurassic Itatskaya suite. The thickness of the Makarovskaya suite, together with sands, ranges between 30–175 m.

The Itatskaya suite (J_2it) is of middle Jurassic age and includes deposits of Aalen, Bayoss, and Bat stages. Rocks of Itatskaya suite are extensive in the characterized territory. They are found at the left bank of the Yenisei River, as well as occupying significant sites on the right bank of the Yenisei River in the basins of the Bolshoi Tel, Maly Tel, Tartat, and Maly Vesnina Rivers. On the left bank of the Yenisei River, rocks of the Itatskaya suite concordantly overlap deposits of the lower Jurassic Makarovskaya suite. Along the Yenisei River right bank and in the vicinity of Pre-Jurassic basement protrusions, the Itatskaya suite transgressively overlaps Precambrian formations. The Itatskaya suite is identified by peculiarities of lithological composition and by the amount of coal present in the lower and upper subsuites. Sediments of the Itatskaya suite along the right bank area of the Yenisei River occupy significant areas at the near-mouth part of the Kan River and in the basins of the Karakchul, Tomna, and Bolshoi Itat Rivers. An ancient Jurassic valley between the Tartat and Orla Rivers is also filled with these deposits. These rocks are characterized by sharp facial variability of lithologic composition and thickness, and it is difficult to separate individual strata. Hence, on the 1:200,000 scale geologic map, the Itatskaya suite in the right bank area of the Yenisei River is shown as undivided. However, sections of the Itatskaya suite are different at various sites of the right bank part of the region. Shingles formed by well-rounded pebbles of igneous and metamorphic rocks with diameters of up to 40 cm occur along the right bank of the Maly Vesnina River in the bottom of the suite. Fine-grained sandstones occur in the Bolshoi Tel River basin in the bottom of the section, whereas the lower part of the Itatskaya suite in the basin of the Tartat River is composed of argillites. Along the right bank of the Bolshoi Tel River, near the village of Novonikolaevka, Jurassic sediments overlie granites.

The lower Itatskaya subsuite J_2it_1 was formerly dated to the Lagerny and Korkinsky horizons. Rocks of this subsuite do not outcrop in the characterized territory. Upper horizons of this subsuite are penetrated only by deep wells in different sites in the region. The most complete section of the lower subsuite is observed to the west of the described region along the left bank of the Yenisei River. Here, rocks of the Makarovskaya suite are concordantly overlain by:

- Shingles, composed of well-rounded pebble of igneous and metamorphic rocks with lenses of yellow-brown obliquely laminated sandstones.
- Obliquely laminated sandstones with shingle lenses in the lower part of the patch.
- Fine-grained, clayey, yellow-grey sandstones with veinlets of greenish aleurolites and blue-grey argillites.

The patch contains two unpersistent beds of brown coal. The upper part of the subsuite is composed of blue-grey argillites, interbedded with green-grey aleurolites and occasionally clayey medium- and fine-grained sandstones of yellow-brown. In this part of the subsuite in the Krasnoyarsk region, there are seven coal beds. The total thickness of the lower subsuite is 260–280 m.

The middle Itatskaya subsuite (J_2it_2) outcrops near the village of Kubekovo at the left bank of the Yenisei River and in the basins of the Buzim and Minzhul Rivers. Rocks of the lower part of this subsuite have no immediate outcrops on the surface of the territory and are penetrated by core wells. A patch of yellow-grey loose sandstones, containing concretions of dense calcic sandstones and occasionally siderites, occurs in the bottom of the middle subsuite. A patch of sandstones is overlain by blue-grey argillites with veinlets of greenish aleurolites, quartz-feldspathic fine-grained sandstones and coaly argillites with 0.3–7.0-m-thick beds of coal. The upper horizons of this patch are traced along Buzim River valley and in the bottom of the outcropping terrace near the village of Kubekovo. The average thickness of the coal-bearing patch is 90–100 m. A typical thickness of the medium subsuite is 130–150 m.

The upper Itatskaya subsuite (J_2it_3) is widespread along the left bank of the Yenisei River. The upper subsuite correlates by its volume with the formerly separate Kubekovskaya stratum. The most complete section of this subsuite can be observed at the Yenisei River bank between the villages of Kubekovo and Khudonogovo. The lower part of the subsuite is composed of friable sandstones containing inclusions of solid (cemented) sandstones. These inclusions often have the form of lenses. The presence of pebbles from subjacent rocks is characteristic for lower horizons of the upper subsuite. The average thickness of the upper subsuite is 100–110 m.

Cretaceous System

Cretaceous sediments are represented mainly by sandstones and clays of the Symskaya suite.

2.2.4 Cenozoic group

The Neogenic system is represented by the Kirnaevskaya suite ($N_1 krn$), dated to the lower Miocene. It extends over the watershed area of the left bank of the Yenisei River, where it discordantly overlaps Jurassic deposits. These rocks are composed of sands and shingles. Their thickness is 30–40 m.

Four groups of Quaternary system deposits form the terrace complexes of the Yenisei River valley. These deposits, as well as clays, loams, and loesses, are widespread in watersheds and valley slopes. Sediments of watersheds and slopes have insignificant thickness and are not distinguished on the geological map. This sedimentation presumably took place over the entire Quaternary period.

Deposits of high terrace complexes, with heights reaching 100 m and more in relation to the waterline of the Yenisei River, are dated to the lower Quaternary (Q_1). The deposits of terrace VIII have a height of 130–140 m, and those of terrace VII have a height of 100–120 m. Terrace VIII is well-defined along the left bank of the Yenisei River between the villages of Kubekovo and Chastoostrovskoe, near the village of Kononovo, and along the right bank of the Yenisei River near the village of Atamanovo. The most complete terrace VIII section is observed near the village of Serebryakovka, where washed-worn socle surfaces are formed by Jurassic rocks. Sediments of the three terraces VI, V, and IV are dated to Middle-Quaternary (Q_2) deposits. The heights of the terraces are 70–80 m for terrace VI, 30–45 m for terrace V, and 20–40 m for terrace IV. Alluvial deposits of terrace VI are widespread near the villages of Kubekovo, Zlobino, and Ust-Batoy. The most complete section of this terrace is observed near the village of Kubekovo. Accumulative sediments of the upper Quaternary (Q_3) group are found in super floodplain terraces of the Yenisei River. These include terrace III, which ranges in height from 15–18 m; terrace II, which ranges from 11–12 m high; and terrace I, which ranges from 7–9 m high. The modern group (Q_4) comprises the very lowest terraces with the heights 5–6 m and 3–4 m over the Yenisei River waterline. These terraces belong to floodplain river formations and correspond to levels of high and low floodplains. The first is flooded at high freshet, and the second is flooded yearly.

2.3 Tectonics

The thickness of the earth's crust in the Yenisei-Kan interfluve region is estimated as 42–45 km. This territory is divided by deep-seated faults of northeastern and northwestern strike, ranging in width of up to a few hundred kilometers. Precambrian, middle Paleozoic, and Meso-Cenozoic structural stages are identified by geologic and structural peculiarities in the upper part of the earth's crust.

2.3.1 Precambrian structural stage

In geologic-tectonic terms, the Precambrian formations belong to the southwestern termination of the Angara-Kan anticlinorium. The structure of the Precambrian Kanskaya and Yeniseiskaya series is investigated as a large anticlinal fold of a northwestern strike overturned at the southwest. The central part of this anticline is formed by Kanskaya series rocks and is broken by Nozhnekanskyi-complex granites, while the southwestern overturned limb is formed by the rocks of Vesninskaya series. The anticline is complicated by the second order folds, often synclinal, typically with a northwestern strike and steeply dipping folded limbs (60–80°) to the northeast and occasionally to the southeast. Third- and higher-order folds are clearly visible along the banks of most large rivers. These folds are overturned and occasionally fan-like, with thicknesses of 20–40 m and dip angles of 60–80°.

Disjunctive disturbances, typically with a northwestern strike, are widespread among the rocks of Kanskaya and Vesninskaya series. The characteristics of these disturbances are determined by their scale. Disturbances of considerable amplitude, traced over large distances, are accompanied by diaphthoresis processes (regressive metamorphism). Kuvayskaya series rocks have meridional or near-meridional strikes maintained over significant distances. Near the village of Barkhatovo these rocks form distinct synclinal folds of meridional strike with an axis plunging to the north and with dip angles of 30–60°. Kuvayskaya series rocks in the zones of tectonic disturbances have been transformed to cataclasites and intensively schistosized.

2.3.2 Middle-Paleozoic structural stage

Devonian deposits forming the Rybinskaya depression and composing this structural stage occupy small areas in the southern part of the region. S2-D1 effusives have gently sloping, almost horizontal, bedding with a weak inclination to the south. Karymovskaya suite conglomerates, widespread in the basins of rivers Tertezh and Temerla, form a syncline with the axis of the northwestern strike. The southwestern limb of this syncline has an inclination of 20–40 °. The northeastern limb is disjunctively cut by the northwestern strike.

2.3.3 Meso-Cenozoic structural stage

Meso-Cenozoic deposits, widespread along the right bank area of the Yenisei River, form the upper structural stage of the West-Siberian epi-Paleozoic platform, and are characterized by weak disturbances. Jurassic deposits have horizontal or slightly inclined bedding with dip angles not exceeding 1 °. In different places, this bedding is complicated by gently sloping folds and waves with fold limb dip angles of 3–5 °. These folds, dome-like and trough-like, are identifiable only by aerial mapping and by tracing of separate beds. The Barabanovskaya trough and the Tatarskyi dome belong to structures of such types. The Barabanovskaya trough (the largest but most weakly expressed structure) has an axis striking to the southeast, and is found on the left bank area of the Yenisei River between the villages of Shivera and Barabanovo. The southwestern limb of this trough is formed by rocks of the upper subsuite of the Itatskaya suite, plunging to the north-northeast with a dip angle of 2–4 °. The Tatarsky dome is a gently sloping fold located near the village of Tatarka. The core of the fold is formed by sandstones of the lower part of the upper subsuite of Itatskaya suite, while limbs are formed by argillites and aleurolites of the upper part of the same subsuite. The dip angles do not exceed 4–5°.

The interrelation between the Jurassic deposits and the rocks of ancient complexes is different in the various parts of the region. Transgressive superposition of Jurassic rocks on Precambrian deposits is observed along the Bolshoi Tel River. Granites and gneisses outcrop here in the lower parts of slopes and in the thalweg of the valley, while elevated sites are composed of Jurassic rocks. At the same time, steep, almost vertical, contact between Precambrian and Jurassic rocks is observed at the Maly Tel River, near the Atamanovsky Ridge, and in the basins of the Tomna, Tartat, and Temerla Rivers. In the immediate vicinity of the contact with Precambrian formations, a horizontal bedding of Jurassic rocks can be seen.

The facts presented suggest that Jurassic deposits can be found both as beds over Precambrian formations, and flanking the more ancient formations (e.g., in the upper reaches of the Bolshoi Itat River). Cretaceous and Neogenic deposits, extending over the left-bank area of the region, transgressively overlap underlying rocks. These have horizontal bedding and form the most elevated watershed sites. Terraces widespread in the Yenisei River basin suggest intense tectonic movements during Quaternary time.

At present, the West-Siberian platform is located significantly lower than the hypsometrically elevated Eastern Sayan and Siberian platforms. Absolute elevations of the platform vary from 90–120 m, and only the southeastern part of the platform reaches 300–370 m. The southwestern border of the Siberian platform is elevated to a level of 500–600 m, whereas the northwestern spurs of the Eastern Sayan platform, located to the south, are even higher, reaching 700–800 m and higher. The hypsometric relationship of the investigated territories has suggested a lowering of the platform in modern times, and, therefore, improved safety with respect to LRW disposal in its sedimentary rock masses. Judging from the thicknesses of separate sedimentary rock masses and from their formation time, the most intensive descending movements in this region of the Western-Siberian platform occurred during the early Cretaceous, in the beginning of the late Cretaceous, and in the Oligocene. During these epochs, the movements varied from approximately 4 mm per thousand years to 19 mm per thousand years.

In the Miocene and early Pliocene periods, sedimentation did not occur in the investigated region. It follows that the southeastern boundary of the West-Siberian platform in the Miocene and Early Pliocene was uplifted and was an area of erosion. The average rate of Miocene-Pliocenic positive tectonic movements, according to O.I. Kupalov-Jaropolk and N.V. Lukina *et al*. (1997), are approximately 4.5 mm per thousand years. In this case, the highest rates of positive tectonic movements of the southeastern part of the West-Siberian platform occurred during Quaternary time.

N.V. Lukina has analyzed river terraces and leveling surfaces of the two largest valleys of the investigated region; namely, the lower parts of the Tom River and the Yenisei River between Krasnoyarsk and the mouth of the Kan River. This work indicates that an intensification of tectonic activity within the limits of the investigated territory has occurred over the last 60,000 years. In this case, the maximum tectonic lifting rates occurred during the Holocene (i.e., during the last 10,000 years). It is significant that West-Siberian platform margins, adjacent to the Kolyvan-Tom folded area, were uplifted somewhat later. Evidently, these platform margins have been falling behind in uplifting pace compared with the joint region of the same Siberian platform where the Yenisei River valley is located. At the first site, tectonic uplift rates during the Pleistocene and Holocene increased from 0.12 mm/yr up to 0.80 mm/yr, while at the second site, rates of up 1 mm/yr occurred (Lukina *et al*., 1990; Kupalov-Jaropolk *et al*., 1997). These latest movements of the crust led to the creation of new disturbances and activation of old rupture disturbances.

Active faults of the investigated territory may be divided into several groups:

- Those active in the Quaternary period and substantiated by displacements of Later Pliocenic leveling surfaces.
- Thos active in the Later Pleistocene and Holocene and substantiated by deformations of leveling relief forms of equal age.
- Those active in present time (modern), where displacements are observed through repeated geodesic measurements or by deformations of the longitudinal profile of the bed of the Yenisei River.

The complex rupture structure of the investigated region was not known during the construction of the LRW disposal site. Neogenic active faults, originating during the last Later Pleistocene-Holocenic stage of tectonic activity, are exemplified by the absence of displacements of deep-seated geological bodies. As a result, their mapping is hampered. Detection of such faults is possible only by displacements of Quaternary sediments or relief forms. Satellite and aerial photographs play an important role in detecting active faults, because they clearly illustrate the displacements of young relief forms and disjunctive deformations of various level surfaces.

A technique of specialized deciphering of active faults shown on satellite and aerial photographs was developed in the Laboratory of Neotectonics and Cosmic Geology of the RAS Geological Institute under the leadership of professor V.G. Trifonov. Using this technique, a map of active faults in 1:200,000 scale was created by N.V. Lukina for the zone of the newer West-Siberian plate and ancient Siberian platform joint at the site of Yenisei-Kan interfluve. In modern times, the junction zone consists of a series of narrow tectonic steps, lowering in succession from east to west, from the hypsometrically elevated Siberian platform to the relatively lowered West-Siberian platform. The Muratovsky Fault plays the role of a boundary seam with a vertical displacement of 4,720 m. This fault limits the western outcrops of the crystalline basement of the Atamanovsky spur of the Yeniseisky ridge. Ancient faults that have been rejuvenated in recent time, such as the Kan-Eniseisky, Malotelsky, and Pravoberezhny Faults, displace the crystalline basement surface by 130–150 m. Neogenic faults typically originate between two rejuvenated ancient faults and have a lesser displacement, on the order of 20–100 m. The Malyi Itatskyi, Bolshoi Itatskyi, Bolshetelskyi, and Atamanovskyi are examples of this type of fault.

2.4 Aquifers

The main water-bearing horizons of Jurassic deposits are Horizon I of the early Makarovskaya subsuite and Horizon II of the middle Itatskaya subsuite. As discussed previously, these are composed of sands and clays. Horizon III, the upper shallow aquifer, is filled with water to a lesser extent and does not occur everywhere. The first and second sandy strata (Horizons I and II) used for disposal occur at depths in intervals of 300–500 m and 180–280 m, respectively. The strata are underlain, separated, and covered by loamy strata, isolating the groundwaters of the strata containing RWs from the surface and from shallow groundwater in Horizon III. Horizon II is marked by a significant amount of vertical inhomogeneity; waste disposal is carried out in the lower third of Horizon II. The areal extent of Horizon I is shown in *Figure 2.5*; the extent of Horizon II is shown in *Figure 2.6*.

Exploration and observation wells provide information on the distribution of geophysical properties and hydraulic heads in the area of the injection site. The network of wells is shown in *Figure 2.7*.

The aquifer horizons are characterized by some vertical inhomogeneity in their flow characteristics, most likely due to subordinate clay and sandy-clay beds in the aquifers. This is illustrated in *Figure 2.8*, which indicates the passage of the waste front through well A58 during injection operations in 1971.

In *Figure 2.8a*, the results of well logging indicate two high permeability bands located at approximately 173 m and 184 m below ground surface (bgs). The waste front broke through these beds on 1 June 1971, soon after beginning injection. The remainder of the beds, between 177 m and 198 m, were filled by the waste front approximately one month later, as can be seen by observations on 2 July. After approximately four months, the waste front had completely broken through in all beds. A somewhat similar picture can be seen in the results of well logging for well A2 (*Figure 2.9*), which is located in Horizon I, close to injection well N2. Two higher-permeability bands are seen at depths of approximately 438 m and 456 m. A third lower-permeability band is seen between 460 m and 467 m.

Results of hydrologic observations are shown in *Table 2.2*, developed from data provided by VNIPIPT (1998). Datum for level measurements is sea level. The locations of these wells are shown in *Figure 2.7*.

Plots of the distributions of these parameters are shown in *Figures 2.10* and *2.11*. These plots represent the interpolation generated by VNIPIPT and used for site calculations. The head contours are based on measurements of the hydraulic head made prior to the beginning of injection in the 1960s and, therefore, represent the steady state condition of the site, undisturbed by injection operations.

Groundwaters in the disposal area are believed to be isolated from the Yenisei River to the west by a fault zone running north-south (shown in *Figures 2.1* and *2.2*).

Examination of the head distribution in Horizon I shows several interesting features related to the fault zone. The significant ($\sim$40 m) difference in heads between the wells on opposite sides of the fault zone indicates that the fault does indeed provide a relatively effective barrier in the region of waste injection. However, the efficiency of the fault zone is questionable in at least two areas. Several kilometers

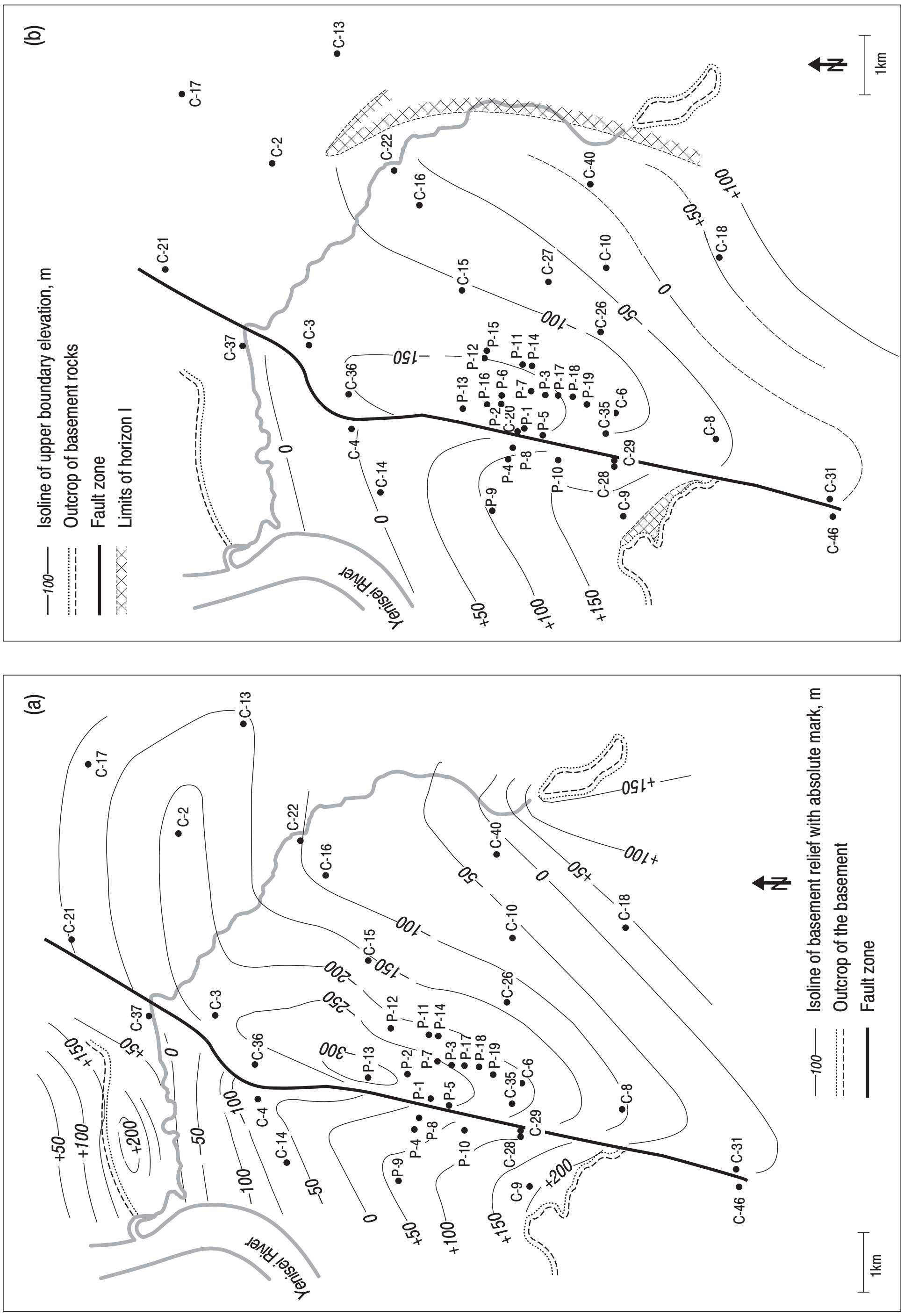

Figure 2.5. Map of (a) basement and (b) top elevations for Horizon I (VNIPIPT, 1998).

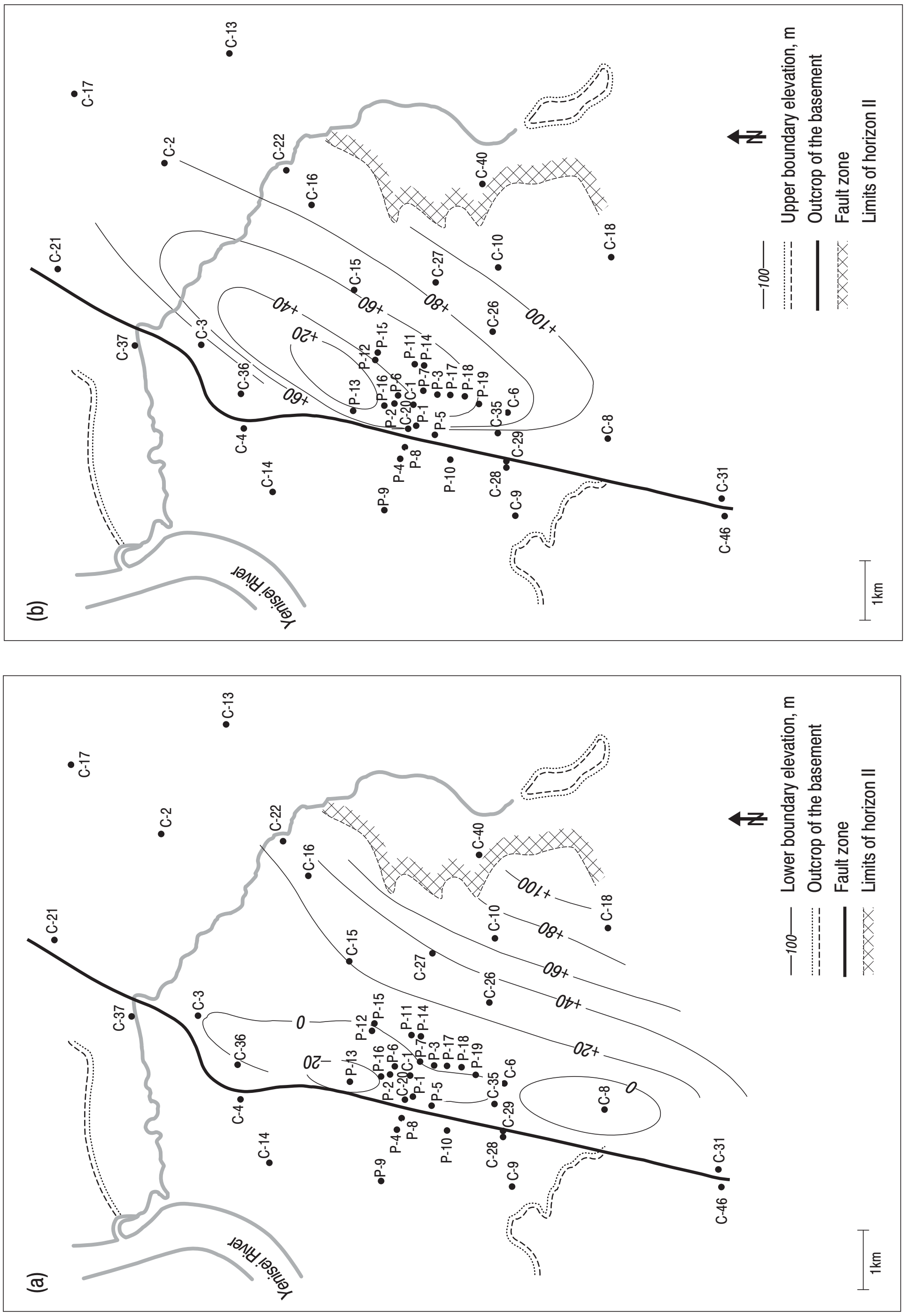

Figure 2.6. Map of (a) basement and (b) top elevations for Horizon II (VNIPIPT, 1998).

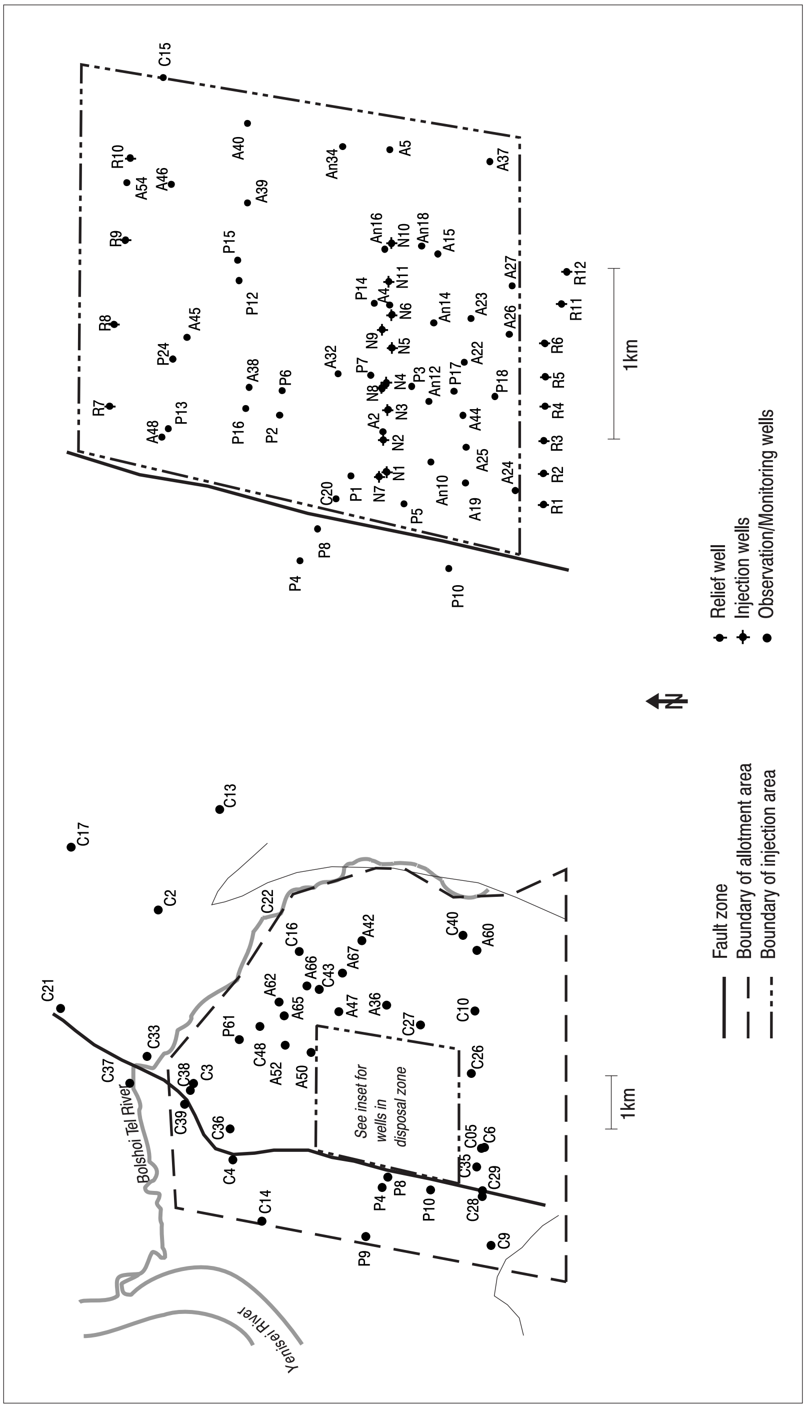

Figure 2.7. Network of wells on the site (VNIPIPT, 1998).

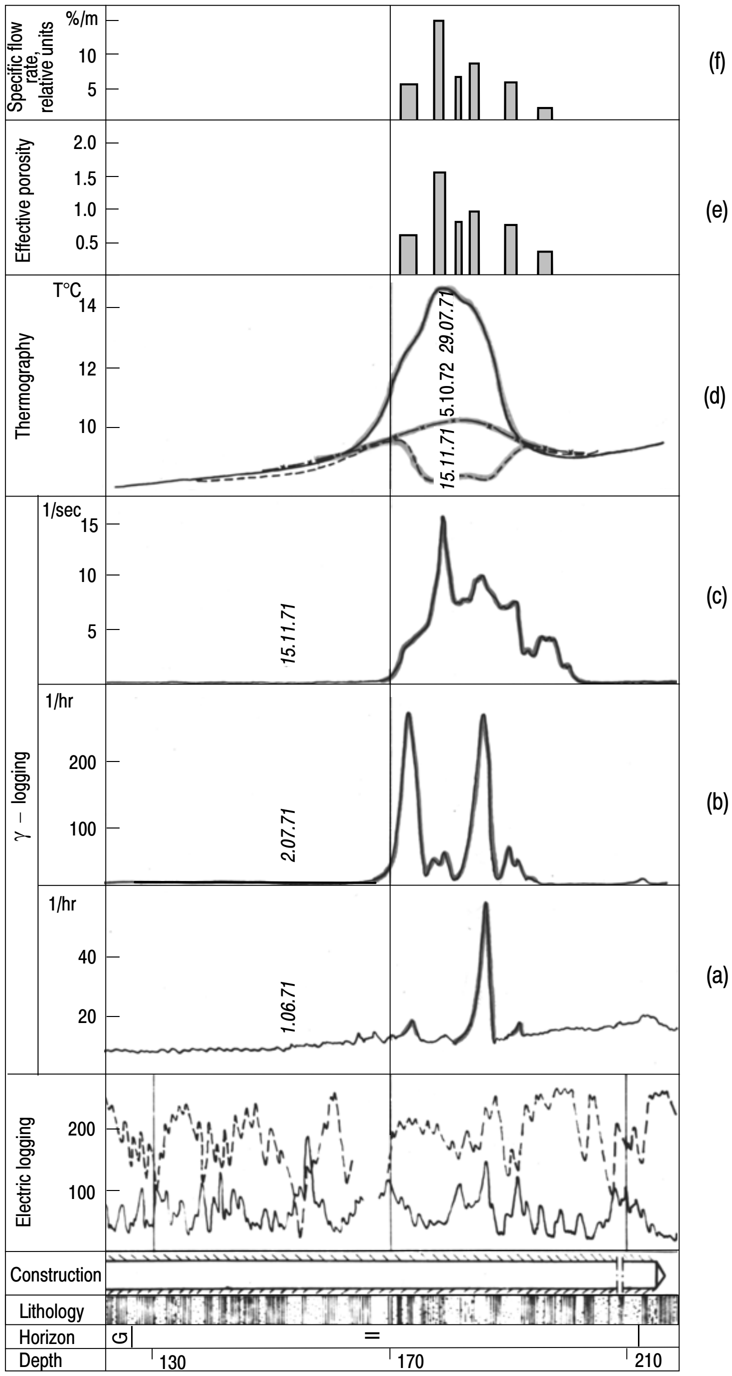

Figure 2.8a. Observations in well A58 (Horizon II): Gamma and thermal logs.

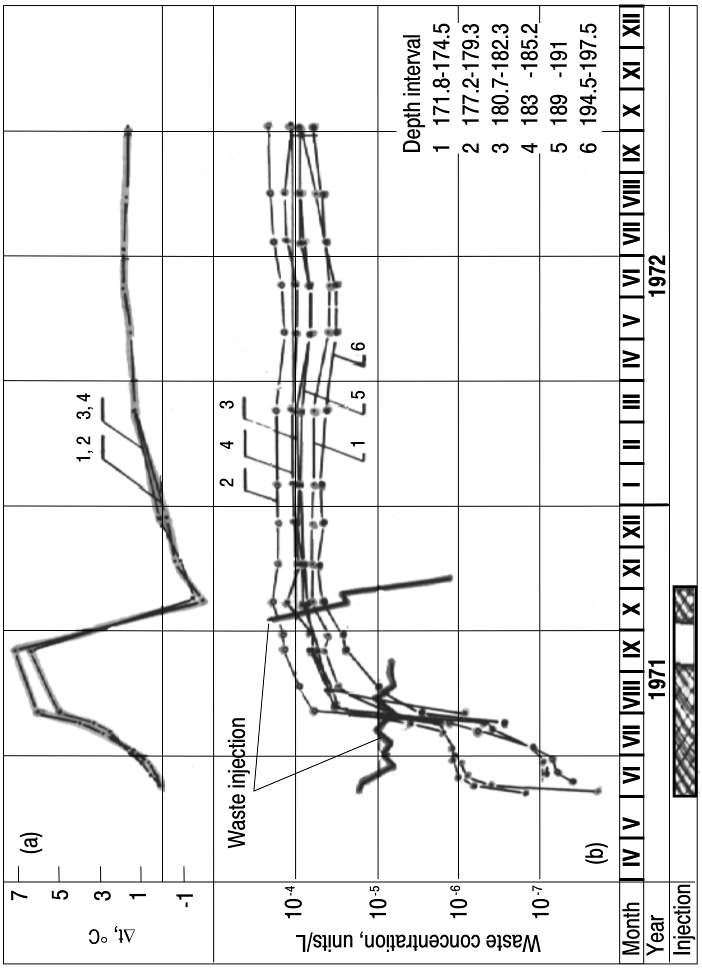

Figure 2.8b. Observations in well A58 (Horizon II): Passage of waste front (VNIPIPT, 1998).

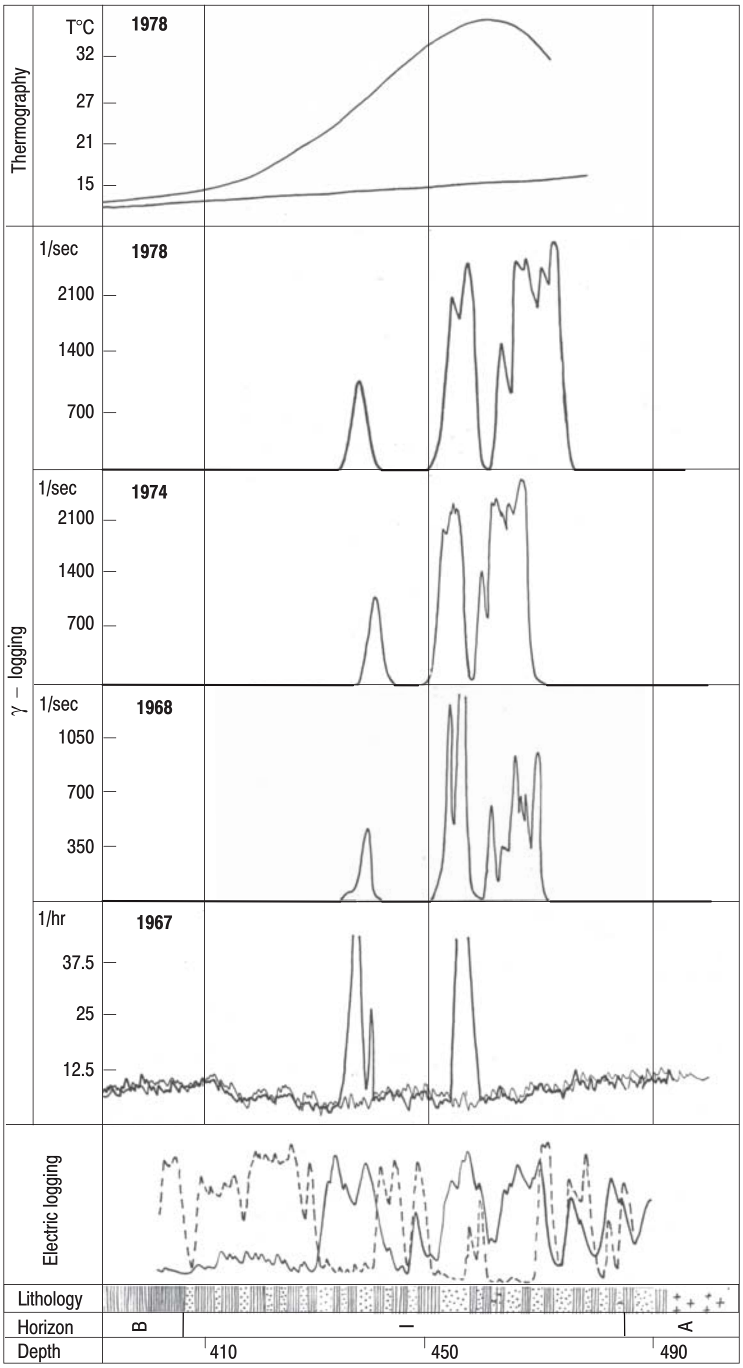

Figure 2.9. Observations in well A2 (Horizon I) (VNIPIPT, 1998).

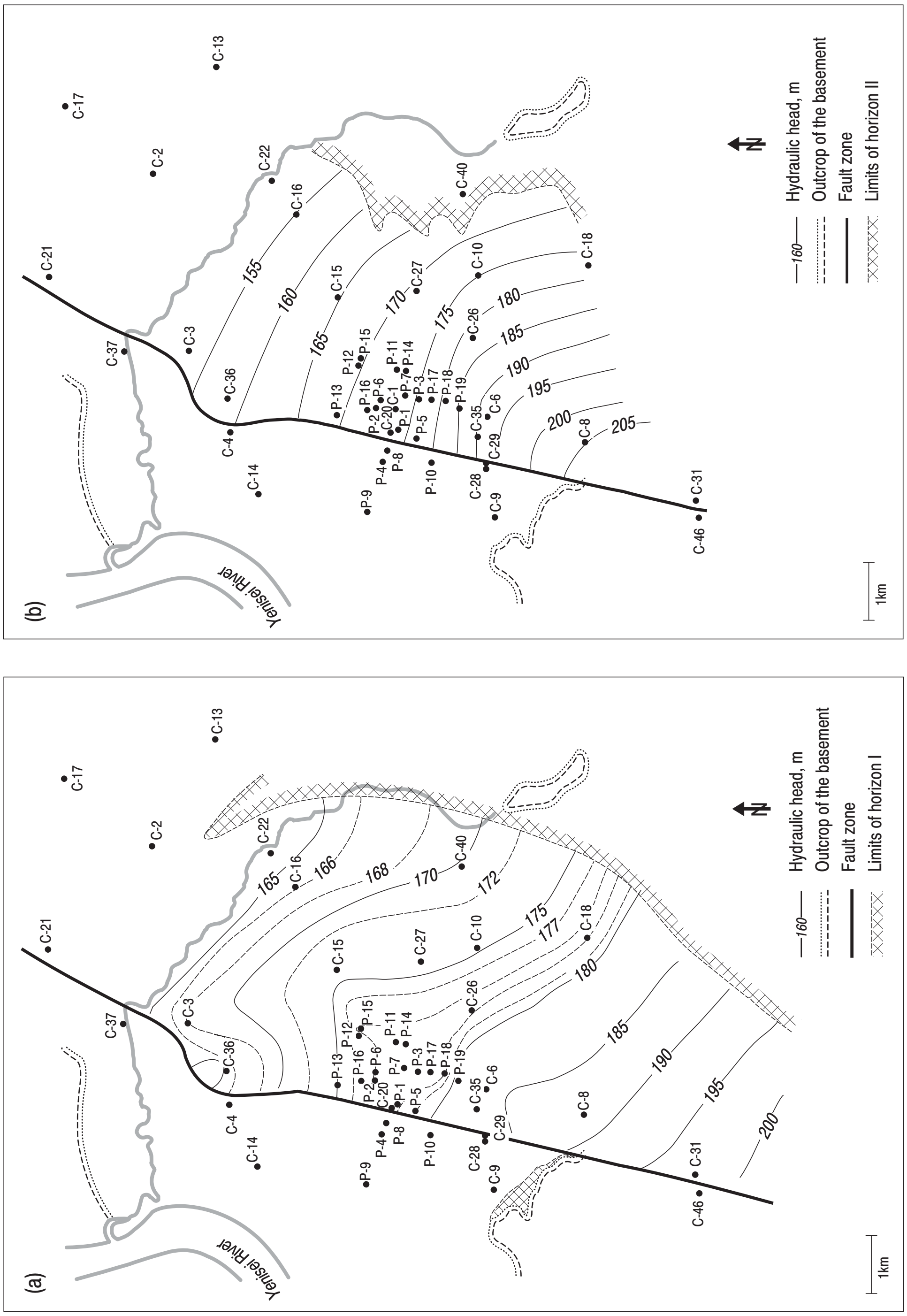

Figure 2.10. Hydraulic head contours: (a) Horizon I; (b) Horizon II.

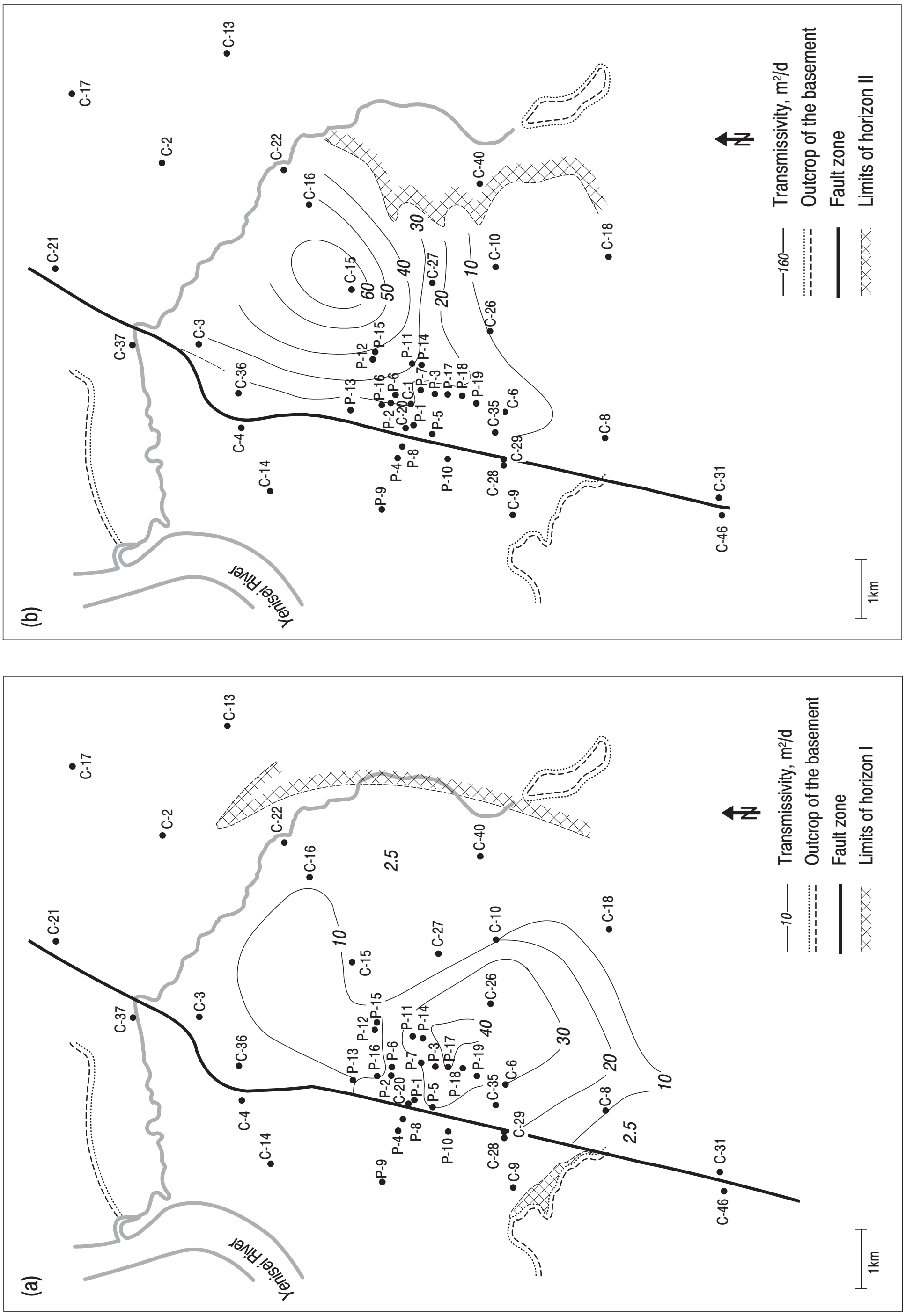

Figure 2.11. Transmissivity contours: (a) Horizon I; (b) Horizon II.

Table 2.2. Results of observations in Horizons I and II (VNIPIPT, 1998).

Well number	Surface elevation (m)	Floor bedrock (m)	Roof (m)	Head (m)	Transmissivity (m^2/day)
Horizon I					
AN-10	236.6				24.2
AN-12	228.7				32.4
AN-14	222.1				35.0
N-03	233.5				22.4
P-01	237.5	−283.0	−172.2	182.3	28.4
P-02	216.4	−276.0	−177.5	182.1	
P-03	228.3	−250.0	−167.3	182.3	
P-04	234.9		97.5	140.4	
P-05	238.2	−233.0	−139.5	182.6	
P-06	210.5				12.3
P-07	230.6		−150.0		
P-08	228.4	−17.0	93.1	140.3	
P-09	224.7	64.0	104.4	140.4	
P-10	239.8	67.0	119.9		
P-11	210.0	−213.5	−144.2		25.6
P-12	197.4	−215.0	−150.5	181.4	5.0
P-13	222.0	−330.0	−188.4	181.3	6.2
P-16	204.1		−180.4		7.8
P-17	229.0				36.3
P-18	231.7		−141.0		26.4
P-19	234.4		−132.9		
C-02	214.2	−223.0	−110.0	165.7	
C-03	159.1	−230.0	−134.0	167.8	1.8
C-04	203.1	−68.0	−0.8	143.7	
C-06	226.5	−202.0	−125.0	183.7	26.0
C-08	242.0	−106.0	−58.7	187.9	3.3
C-09	247.1	177.0	187.6	216.1	
C-10	171.9	−67.0	−40.6	178.8	
C-13	254.8	−171.0	46.2	166.5	
C-14	189.8	−71.4	6.7	141.6	
C-15	212.8	−160.5	−110.7	174.2	7.7
C-16	158.6	−92.0	−71.8	165.5	
C-17	228.9	−114.5			36.3
C-18	180.0	44.0	53.5	177.5	2.7
C-20	234.4	−247.0	−152.9		
C-21	208.9	−100.5		163.1	
C-22	145.3		−58.3	160.5	
C-26	210.1		101.7		33.0
C-28	238.2		109.4	190.1	
C-29	236.5		100.0	163.7	
C-31	218.0		−4.0	197.9	
C-35	220.7		−97.8		22.5
C-36	203.0			165.8	
C-37	136.4		−14.5	140.8	
C-40	164.3		0.7	169.9	
C-46	239.2			230.4	

Table 2.2. Continued.

Well number	Surface elevation (m)	Floor bedrock (m)	Roof (m)	Head (m)	Transmissivity (m^2/day)
Horizon II					
P-01	237.5		45		55.3
P-05	238.2		109		
P-06	210.5		36	172.2	
P-07	230.6		42	173.6	
P-10	239.8				24.9
P-11	210.0				15.8
P-13	222.0		26	170.0	
P-14	218.0		53		
P-15	188.8		48	169.2	
C-01	237.4		37	174.1	
C-02	214.2				17.6
C-03	159.1		80	153.6	
C-04	203.1				38.9
C-06	226.5		67	192.3	
C-08	242.0		30	205.3	
C-10	171.9			174.2	
C-15	212.8		62	164.7	
C-16	158.6		45	154.4	
C-17	228.9				17.5
C-20	234.4				25.1
C-26	210.1		87		
C-27	189.6		89		
C-28	238.2				14.4
C-29	236.5				6.1
C-35	220.7		111		
C-35	220.7				0.8
C-36	203.0		96		
C-46	239.2				70.9

south of the site, in the region of wells C-28 and C-29, there is a very strong depression in the head levels of the upthrown block, with head differences of 27 m over only a few kilometers. There is a corresponding elevation in the heads of the downthrown block, indicating that subsurface waters may possibly feed through the fault from the upthrown block to the downthrown block. Approximately 3 km north of the site, there is an anomalously low water level in well C-36, and a correspondingly high anomaly in well C-4 of the upthrown block. This indicates that there may be a potential for waters of the downthrown block, containing the wastes, to communicate with waters of the upthrown block, which may discharge to the Yenisei.

Several factors, however, indicate that the fault zone acts as an effective barrier to water flow in the vicinity of the disposal zone:

- The difference in water heads ($\sim$40 m) in wells on opposite sides of the fault zone.
- The results of pumping tests carried out that indicate no response in wells on opposite sides of the fault zone.
- The results of interpolation of water heads, which indicate that flow lines do not cross the fault zone in the region of waste disposal.
- The elevation difference between the upthrown and downthrown blocks. Near the disposal zone, Horizon I is in contact only with the crystalline rocks of the upthrown block, as seen in *Figure 2.2*.

2.4.1 Recharge and discharge areas

There is some debate regarding the location of the recharge and discharge areas of the disposal horizons at the Severny site. Rybalchenko *et al*. (1994), based on official data gathered over 30 years of site operation, reports that the recharge area of Horizon I is 7 km to the south of the Severny site. Groundwater in Horizon I travels northward at 5–6 m/yr under the influence of a hydraulic gradient of 0.003. The recharge area of Horizon II is reported to be located 4–5 km to the south from Severny site. Green Cross (Robinson and Volosov, 1996) reports that the two aquifers have a common recharge area located 10–15 km south of the disposal area. The flow in Horizon II is believed to be approximately 10–15 m/yr. Of greater concern for the safety of the disposal site is the discharge area of the horizons. Rybalchenko *et al*. (1994) states that the main discharge area of Horizon I is to the Kan River, 12–14 km north of the site, and that Horizon II discharges partially to the Kan River and partially to the Bolshoi Tel River. Green Cross (Robinson and Volosov, 1996) reports that there is a flow of artesian waters from Horizon I to Horizon II in the region of the Bolshoi Tel near wells C-16 and C-22, several kilometers northeast of the disposal site. As will be discussed in a subsequent section, it appears that there may be discharge of Horizon I to Horizon II, and, subsequently, to the Bolshoi Tel. There is as yet no unambiguous answer to the question of the location of the discharge area of Horizon I.

2.4.2 Groundwater properties

The waters of both Horizon I and II are generally fresh, with salt contents less than 0.3 g/L. Green Cross (Robinson and Volosov, 1996) reports that the waters of Horizon I have a sodium-hydrocarbonate composition with mineralization up to 0.5 g/L, and that the waters of Horizons II and III have a calcium-magnesium-hydrocarbonate composition with mineralization between 0.3–0.4 g/L.

Table 2.3. Summary table of horizon properties.

Property	Horizon I	Horizon II (lower third)
Depth, m bgs	355–500	180–280
Composition	Gravel sands, breccias; nonsorted brecciated rocks with limestone cement	Arkosic sands, sometimes highly carbonaceous with interbeds of clays
Thickness, m	55–85	25–45
Effective thickness, m	25–35	23–45
Total porosity	0.2–0.25	0.3
Effective porosity	0.07	0.08–0.12
Transmissivity, m^2/day	5–40	20–80
Hydraulic conductivity, m/day	0.3–1.6	0.1–2.2
Gradient	0.003	
Groundwater velocity, m/yr	5–6	10–15
Recharge area[b]	7 km to the south	4–5 km to the south
Discharge area	Kan River, 12–14 km north of the site[c]	Partially to the Kan River and partially to the Bolshoi Tel river
Groundwater properties[a]	Sodium–hydrocarbonate composition with mineralization up to 0.5 g/L	Calcium–magnesium–hydrocarbonate composition with mineralization between 0.3–0.4 g/L

[a] Robinson and Volosov (1996).
[b] Robinson and Volosov (1996) reports that the two aquifers have a common recharge area located 10–15 km south of the storage ground.
[c] The discharge area of Horizon I is a matter of some debate, as discussed in later sections of the report. The information presented here is based on Rybalchenko *et al.* (1994).

2.4.3 Summary of geology and hydrology

A summary table of the properties of the two disposal strata are given in *Table 2.3*.

2.5 Waste Characteristics

Three types of wastes are injected underground at the Severny site. Process wastes, injected into the deep Horizon I, are comprised of high-level acidic wastes and medium-level alkaline wastes. There are some indications that some ILW have been disposed of in Horizon II. Process wastes contain sodium salts, silica gels, and metallic contaminants. Acidic, high-level process wastes have salt contents of 250–350 g/L with a pH range of 1–3. The chemical composition includes nitrates, soluble complexes of heavy metals from corrosion products (iron, chromium, manganese, and nickel), and complex forming reagents. Alkaline process wastes have a

Table 2.4. Estimates of injected waste properties at Krasnoyarsk, decay corrected to 1 January 1995.

	Low activity waste	High activity waste	Intermediate activity waste
Total volume ($10^6 m^3$)	2.78	0.068	2.14
Sum of activity as of 1 January 1995 (Bq)	5.7×10^{14}	4.2×10^{18}	5.4×10^{18}
Specific activity as of 1 January 1995 (Bq/L)			
^{90}Sr	4.8×10^{4}	4.4×10^{10}	7.5×10^{7}
^{137}Cs	1.5×10^{4}	3.0×10^{9}	2.3×10^{9}
^{95}Zr, ^{95}Nb, ^{103}Ru, ^{106}Ru, ^{144}Ce, others	7.4×10^{4}	1.5×10^{10}	
^{99}Tc		3.0×10^{5}	3.0×10^{5}
^{135}Cs		1.1×10^{4}	9.2×10^{3}
^{239}Pu	37	8.1×10^{4}	1.3×10^{5}
^{237}Np		5.6×10^{3}	
^{241}Am		7.0×10^{5}	
Total	2.0×10^{5}	6.2×10^{10}	2.5×10^{9}

salt content of 30–350 g/L. The chemical composition includes nitrates and soluble complexes of aluminum and silicon. As of 1995, the HLW was localized within 200–250 m of wells N-2 and N-3, occupying an area of 22 hectares (ha); the ILW was localized within 300–500 m of the line of injection wells, occupying approximately 140 ha (Bradley, 1997). Nonprocess wastes injected into the lower third of Horizon II generally comprise LLWs. These wastes contain salts and detergents and are weakly alkaline, with a salt content of 1–30 g/L. As of 1995, these wastes occupied an area of 190 ha (Bradley, 1997).

2.5.1 Inventories

An accurate characterization of the wastes injected at the site over its operational history is not yet available. Several sources provide indications of the characteristics of the waste disposed. *Table 2.4*, provided by Radleg and based on analyses conducted by the RAS Institute of Physical Chemistry, indicates the amount and characteristics of the wastes disposed. The Radleg project has and continues to produce the most comprehensive database of radioactive waste in Russia. The first publication will be an IIASA book entitled *The Radiation Legacy of the Soviet Nuclear Complex* in 2000.

For comparison, the values reported in Robinson and Volosov are also given in *Table 2.5*, since these also give information on levels of chemical components in the waste.

Table 2.5. Green Cross estimates of injected waste properties at Krasnoyarsk (Robinson and Volosov, 1996).

Components	Process wastes Nitrate (HLW)	 Alkaline (ILW)	Nonprocess wastes (LLW)
Chemical components (g/L)			
$NaNO_3$	100–150	120–360	4–20
H Ac + Na Ac	10–20	3–14	
HNO_3	0.5–20		
Na_2CO_3 + Na HCO_3		1.5–3.0	0.5
NaOH		1–16	<0.3
Al(III+)	0.15	1.5–3.0	
Fe(III+)	0.3		
Cr(III+, VI+)	0.5	0.2	
Mn(II+)	0.3		
Ni(II+)	0.3		
PAV(OP–7)			0.03
TBP	0.05	0.03	
Radionuclides (Bq/L)			
^{90}Sr	7.4×10^{10}–1.1×10^{11}	1.9×10^{7}	1.1×10^{5}
^{137}Cs	1.1×10^{10}	3.7×10^{9}–1.5×10^{10}	1.5×10^{5}
^{144}Ce	2.8×10^{11}		3.7×10^{4}
^{106}Ru	3.7×10^{10}	3.7×10^{9}	3.7×10^{4}
Total Beta	1.1×10^{11}–7.8×10^{11}	3.7×10^{8}–1.9×10^{10}	7.4×10^{4}–1.9×10^{6}
Transuranium elements (μg/L)			
^{239}Pu	100–500	10–30	<1
^{241}Am	170	–	–
^{237}Np	400	–	–
^{232}Th	200–300	–	–

2.5.2 Physical properties of wastes

One of the key safety features of the repository is the sorptive ability of the host rock in the repository. Radionuclides are believed to be strongly sorbed to the rocks, thus binding the hazardous constituents of the waste for a sufficient time to allow for radioactive decay. Based on the results of sorption studies commissioned by the site, many of the nuclides are believed to be relatively permanently bound to the host rock, with a limited degree of desorption. *Table 2.6* is derived from Rybalchenko *et al.* (1994), and indicates the characteristics and retentive properties of typical Russian reprocessing wastes.

The pH of the waste liquid strongly affects the sorptive properties. This can be seen in *Table 2.7*, showing the distribution coefficient for important nuclides as a function of pH and ionic strength of the waste liquid.

Table 2.6. Waste form interaction with geologic media.

Nuclide	C_0/C_{DCb}	Distribution coefficient, K_D (cm^3/g)	Retardation factor (R)	Desorption (%)
Acidic process wastes				
^{90}Sr	1.0×10^9	1.2–1.3	6–9	21–22
^{106}Ru	7.0×10^7	1.3–1.6	6–7	0.5–1.2
^{137}Cs	2.0×10^7	2.7–2.8	13	0.7–1.3
^{144}Ce	6.5×10^8	1.0–1.6	4–8	12–19
^{237}Np	100	1.8–2.3	9–11	8–40
^{239}Pu	1,000	1.4–1.6	13–30	0.5–3.0
^{241}Am	10,000	1.1–1.2	5–6	18–20
Alkaline process wastes				
^{90}Sr	2.5×10^8	5.5–7.0	26–33	16–31
^{106}Ru	6.7×10^6	6.0–10.5	30–50	12–30
^{137}Cs	6.0×10^6	4.5–6.5	30	11–13
^{239}Pu	140	40–95	200–460	10–15
Weakly alkaline nonprocess wastes				
^{90}Sr	5,000	35–37	200–300	5.5–9.0
^{106}Ru	900	7–14	45–85	1.4–4.0
^{137}Cs	270	60–90	350–450	1.5–2.0
^{144}Ce	80	–	95–115	1.5–4.0
^{239}Pu	10	110–140	500–625	3–6

Table 2.7. Properties of wastes in sand-clay rocks.

	K_D (cm^3/g)			
Nuclide	pH = 2–3 μ = 1.0	pH = 4–5 μ = 1.0	PH ∼8 μ = 1.0–0.2	pH ∼8 μ = 1.0
^{90}Sr	1.5–5.5	10–35	7–10	20–30
^{106}Ru	0.5–1.5	7.5–15	2–2.5	4.6–7.5
^{137}Cs	1.5–3.0	10–20	8–15	20–50
^{144}Ce	1.0–1.5	40–100	5–10	9.5–19
^{239}Pu	1.2–1.6	50–120	5–12	15–35

IIASA did not perform a detailed calculation of the energy output of the wastes. Such an analysis would require a much more extensive characterization, including all of the short-lived radionuclides. However, an idea of the heat generation of the wastes can be determined from data in *Table 2.8*. As this table uses the same relative ratios of isotopes for all classes of wastes, it is clearly not a precise picture of the energy output; however, it does give an indication of the heat output of the wastes.

Table 2.8. Energy output of wastes.

Nuclide	Parent half-life (years)	Decay energy (MeV[a])	Content (%)	Energy output (W/m^3) 0 years	1 year	10 years
^{90}Sr + ^{90}Y	29.12	1.126	23	0.79	0.77	0.60
^{95}Zr + ^{95}Nb	0.18	1.655	1	0.04	<0.01	~0
^{106}Ru + ^{106}Rh	1.01	1.615	22	1.07	0.54	~0
^{137}Cs + ^{137}Ba	30	0.745	14	0.31	0.30	0.24
^{134}Cs	2.06	1.72	9	0.46	0.33	0.01
^{144}Ce + ^{144}Pr	0.78	1.34	24	0.98	0.4	~0
^{147}Pm	2.62	0.064	7	0.01	<0.01	~0
Total			100	3.66	2.35	0.85

[a] MeV = mega-electron volt.

Table 2.9. Summary table of injected waste properties.

Property	Process wastes HLW	HLW/ILW	Nonprocess wastes LLW
Total volume (10^6m^3)	0.068	2.2	2.78
Sum of activity (Bq) as of 1.1.95	4.2×10^{18}	9.6×10^{18}	5.7×10^{14}
Total specific activity, Bq/L	6.2×10^{10}	4.1×10^{9}	2.0×10^{5}
pH	1–3	Alkaline	Weakly alkaline
Salt content, g/L	250–350	30–350	1–30
Chemical composition	Nitrates; soluble complexes of heavy metals from corrosion products (iron, chromium, manganese, and nickel); complex forming reagents.	Nitrates; soluble complexes of aluminum and silicon	Salts, detergents
Estimated area of waste contour[b,c] (ha)	22	140	190

[a] Energy output based on generic waste form with waste composition as in *Table 2.8*.
[b] As of 1995.
[c] Robinson and Volosov, 1996.

2.5.3 Summary of waste characteristics

Table 2.9 gives a summary of the wastes injected at the Severny site.

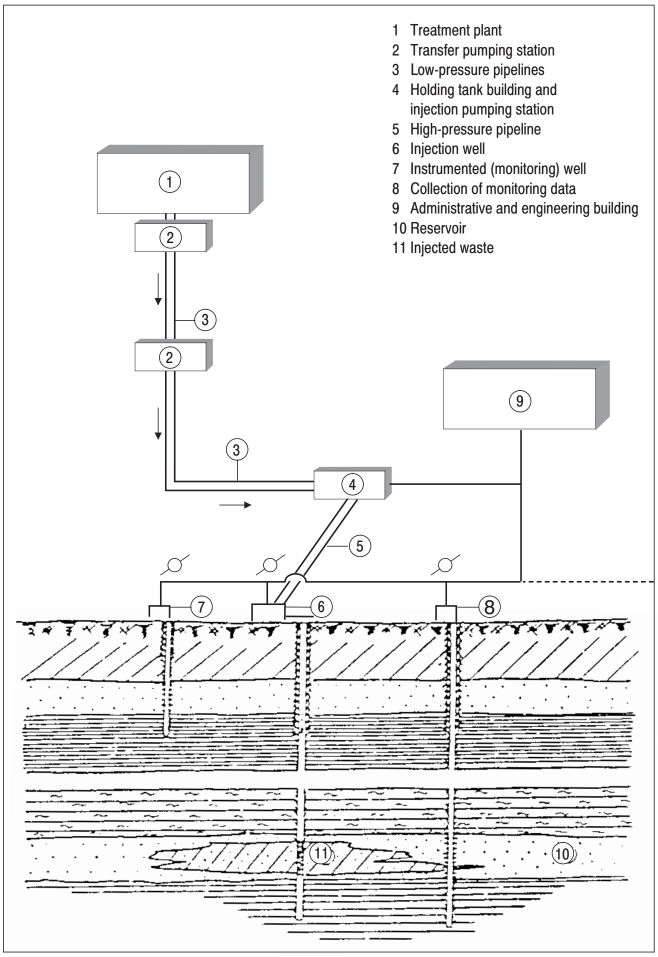

Figure 2.12. Conceptual representation of injection facilities (Rybalchenko *et al.* 1994).

2.6 Disposal Site Construction and Operation

2.6.1 Operational facilities

The injection facility comprises a system of transfer pipelines, injection, relief, monitoring and observation wells, and monitoring equipment. A conceptual representation of the site is shown in *Figure 2.12*.

Two pipelines, one for process wastes and one for nonprocess wastes, are used to transfer wastes to the injection site. Several types of wells are used, including injection wells, relief wells, geophysical wells, and observation/monitoring wells. The design of the wells is shown in *Figure 2.13*.

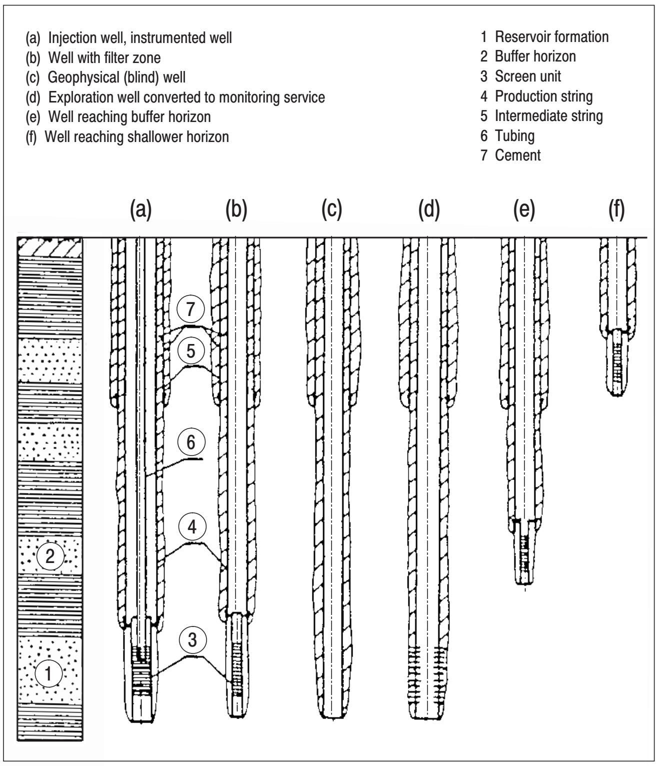

Figure 2.13. Design of wells at the Severny injection site (Rybalchenko *et al.* 1994).

High- and Medium-Level Waste Disposal Facilities

The high- and medium-level facility comprises eight injection wells, eight relief wells, and 54 monitoring and observation wells. Process salt solutions are transferred to the disposal site by a 6-in.-dia. pipeline made of IX18H10T steel located in a sealed ferroconcrete tray and buried at a depth of 3 m (Robinson and Volosov, 1996). The tray is lined with corrosion-resistant materials and flexible plastic. The transfer lines are equipped with leak-catching vessels with level alarms and drains located along the route of the pipeline. The wastes are transferred under low pressure and are sloped to provide gravity drainage to the site. There are two intermediate pumping stations located along the pipeline.

Wastes are typically treated at the source prior to transfer to the injection site. Wastes are received at the injection site and discharged into holding tanks, which allow settling of the wastes. Sampling is carried out prior to transfer from the radiochemical plant; personnel at the injection site verify the waste composition with samples of each batch. The injection pumps are Russian BEN and TsNG series glandless pumps capable of delivering injection pressures of between 10–25 atm of gage pressure. These pumps are housed in pavilions with automatic heating systems and balanced ventilation systems that include air purification equipment.

Alkaline process wastes are injected through wells N-4, N-5, and N-6 into Horizon I. Injection rates of ILW can be up to 300 m^3/day, with an injection pressure of 1.2 MPa. Injection of high-level process wastes, due to their smaller volume, is not carried out regularly. These nitrate process wastes are injected through wells N-2 and N-3, in batches of 1,000–2,000 m^3, one or two times a year. HLW disposal has been carried out since 1972. Relief wells located approximately 1 km south of the site are used to relieve pressure buildup in the horizon, and produce up to 300 m^3/day.

Low-Level Waste Disposal Facilities

The low-level waste facility is comprised of four injection wells, four relief wells, and 37 monitor wells. Low-level nonprocess wastes are transferred to the disposal site by a pipeline made of IX18H10T steel that is laid in an earthen trench. Sampling is carried out prior to transfer from the radiochemical plant. The pipeline has one pumping station. Wastes are typically treated prior to transfer to the injection site. Wastes are received at the injection site and discharged into holding tanks, which allows settling of the wastes. The waste composition is verified by periodic sampling of the wastes received at the injection site. Centrifugal pumps are used for injection, with stuffing boxes, capable of delivering injection pressures of 20–60 atm gage pressure. These pumps are housed in pavilions with automatic heating systems and balanced ventilation systems that include air purification equipment. The wastes are pumped through wells N-7, N-8, N-9, N-10, and N-11 into Horizon II. Wastes are injected relatively constantly throughout the year, beginning in the spring and ending in the fall. Injection is carried out at rates of up to 600 m^3/day and at injection pressures of up to 2.0 MPa. The relief wells for Horizon II, located 1 km north of the injection array, are not used since the pressure is relieved fairly quickly by horizontal migration. Heads in wells in the vicinity of the injection area demonstrate a regular rise during operation of the injection wells.

Summary of Operational Features

Table 2.10 gives a summary of the facilities for waste disposal at the Severny site.

Table 2.10. Summary table of Severny operational characteristics.

	HLW	ILW	LLW
Period of operation	1972 to present	1967 to present	1968 to present
Disposal horizon	I	I	II
Waste source	Acidic process wastes	Alkaline process wastes	Nonprocess wastes
Transfer pipeline[a]	6-in.-dia., IX18H10T steel pipe located in a sealed ferroconcrete chute and buried at a depth of 2–5 m	6-in.-dia., IX18H10T steel pipe located in a sealed ferroconcrete chute and buried at a depth of 2–5 m	IX18H10T steel pipe located in an earthen trench
Pretreatment	Preinjection of weakly acidic solutions to cut down on nuclide buildup on the formation. Conversion of less soluble forms to soluble complexes		
Injection wells	N-2 and N-3	N-1, N-4, N-5, N-6 and N-11	N-7, N-8, N-9, and N-10
Injection rates	1,000–2,000 m^3 batches	Up to 300 m^3/d	Up to 600 m^3/d
Injection frequency	One to two times per year	Regularly from spring through fall	Regularly from spring through fall
Injection pressure	Free-flow injection	1.2 MPa	2.0 Mpa
Relief wells	R1–R6, R11, R12; ∼1 km to the south	R1–R6, R11, R12; ∼1 km to the south	R7–R10 (not used); ∼1.5 km to the north
Observation and monitoring wells	54	54	37

[a] Robinson and Volosov, 1996; Bradley, 1997.

2.6.2 Monitoring and sampling

Facility Monitoring

Monitoring is the responsibility of the site operations office and is carried out at the Severny site for several reasons, including:

- Verifying the absence of wastes or contamination outside the exclusion zone.
- Validating the results of predictive models of waste dispersal.
- Checking the physical integrity of the injection facilities.
- Checking the composition of the injected wastes.

Table 2.11. Observation well data, Horizons I and II (VNIPIPT, 1998).

Well number	Nitrate (mg/L)	Radionuclide (Bq/L)	Tritium (Bq/L)	Gamma ray logging (μA/kg)
Horizon I				
A-02	–	–	–	4,600,000
A-04	–	–	–	5,600,000
A-05	0.84	<3	<30	nat
A-15	8.9	10	1,000	nat
A-19	0.42	<3	<30	nat
A-22	0.53	<30	<30	nat
A-23	4,090	150	7,500	21
A-24	0.9	<3	<30	nat
A-25	0.44	5	–	10.5
A-26	0.44	<3	<30	nat
A-27	0.44	<3	<30	nat
A-32	2,300	<3	<30	nat
A-37	<0.3	<3	–	nat
A-45	<1	<3	<5	nat
AN-10	4,400	120	5,500	17
AN-12	51,400	4,440	–	370
AN-14	9,800	1,630,000	–	3,100,000
AN-18	1,200	120,000	–	2,500
P-01	2,400	25	5,600	44
P-04	0.7	<3	–	nat
P-08	0.75	<3	–	nat
P-10	<0.3	<3	–	nat
P-11	29,600	3,600	–	4,400,000
P-12	0.75	<3	<30	nat
P-16	1.8	<4	<5	nat
P-17	1.2	<3	<30	nat
P-18	0.3	<3	<30	nat
P-19	1.4	<3	<30	nat
C-26	<0.3	<3	–	nat
C-28	<0.3	<3	–	nat
C-29	<0.3	<3	–	nat
C-35	<0.3	<3	<30	nat

Note: nat = natural background.

Table 2.11. Continued.

Well number	Nitrate (mg/L)	Radionuclide (Bq/L)	Tritium (Bq/L)	Gamma ray logging (μA/kg)
Horizon II				
A-11	1.2	<3	–	nat
A-18	13.2	30	690	nat
A-36	–	–	–	nat
A-38	2.7	<3	<30	nat
A-39	1.1	<3	<30	nat
A-44	3.7	<30	80,000	14.5
A-46	1.6	<3	<30	nat
A-47	<0.3	<3	–	nat
A-57	2.8	480	400,000	nat
AN-31	0.88	<30	<30	nat
AN-33	742	<10	20,000	nat
AN-34	1.6	7	230	nat
D-01	0.44	<3	<30	nat
D-02	1.8	<3	<30	nat
D-03	<0.3	<0.2	<30	nat
D-04	<0.3	<3	<30	nat
N-08	–	–	–	260,000
N-09	–	–	–	90,000
N-10	–	–	–	600,000
P-02	2.1	<4	–	nat
P-05	–	–	–	–
P-06	–	–	–	–
P-07	68	<9	–	nat
P-13	1.9	<4	<30	nat
P-14	0.3	<3	–	nat
P-15	1.3	<3	<30	nat
P-20	<0.3	<3	–	nat
C-01	492	<5	3,300	nat
C-06	<0.3	<2	<30	
C-15	2.1	<3	–	nat
C-20	0.42	<3	–	nat
C-27	0.79	<4	–	nat

Note: nat = natural background.

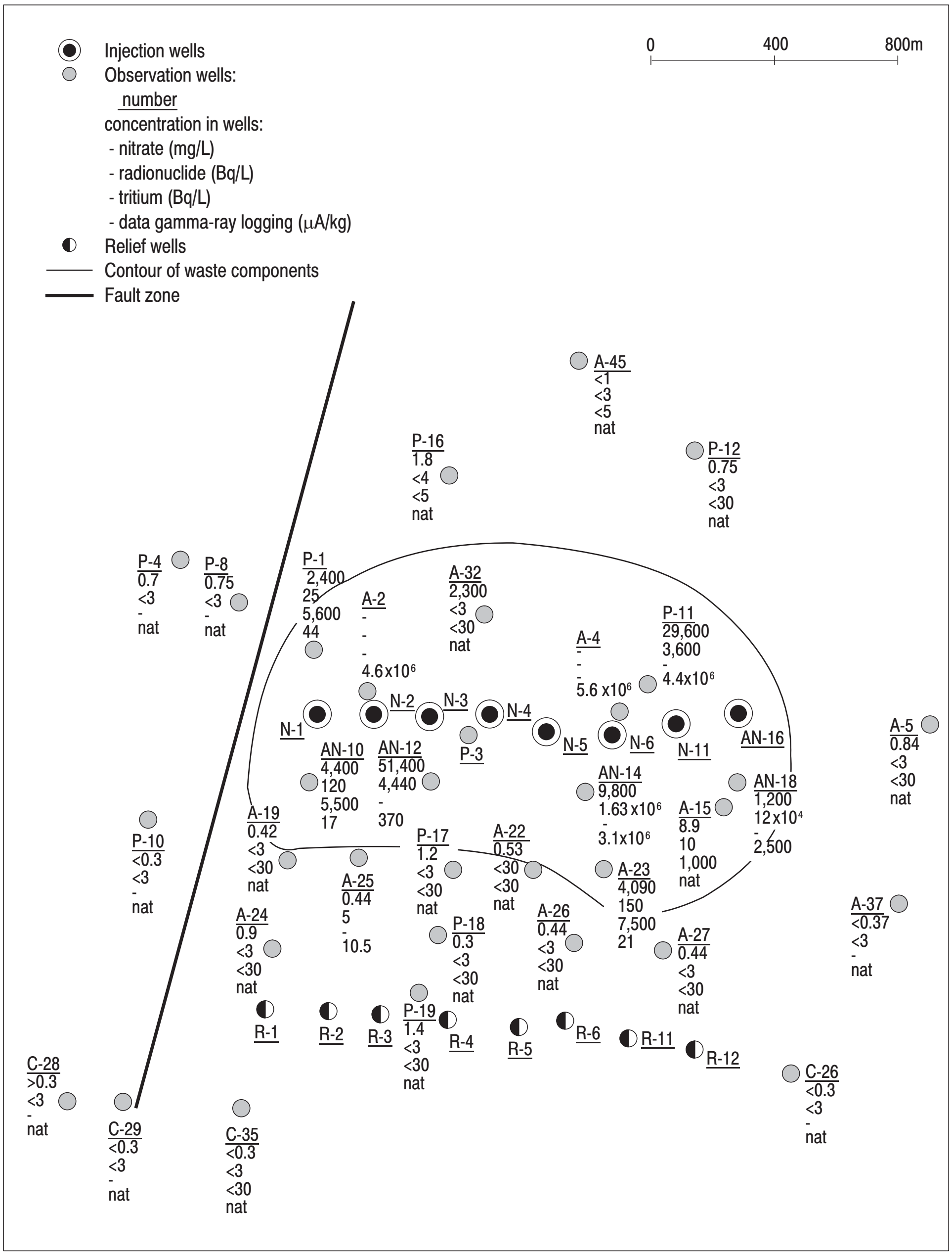

Figure 2.14a. Results from monitoring wells in Horizon I.

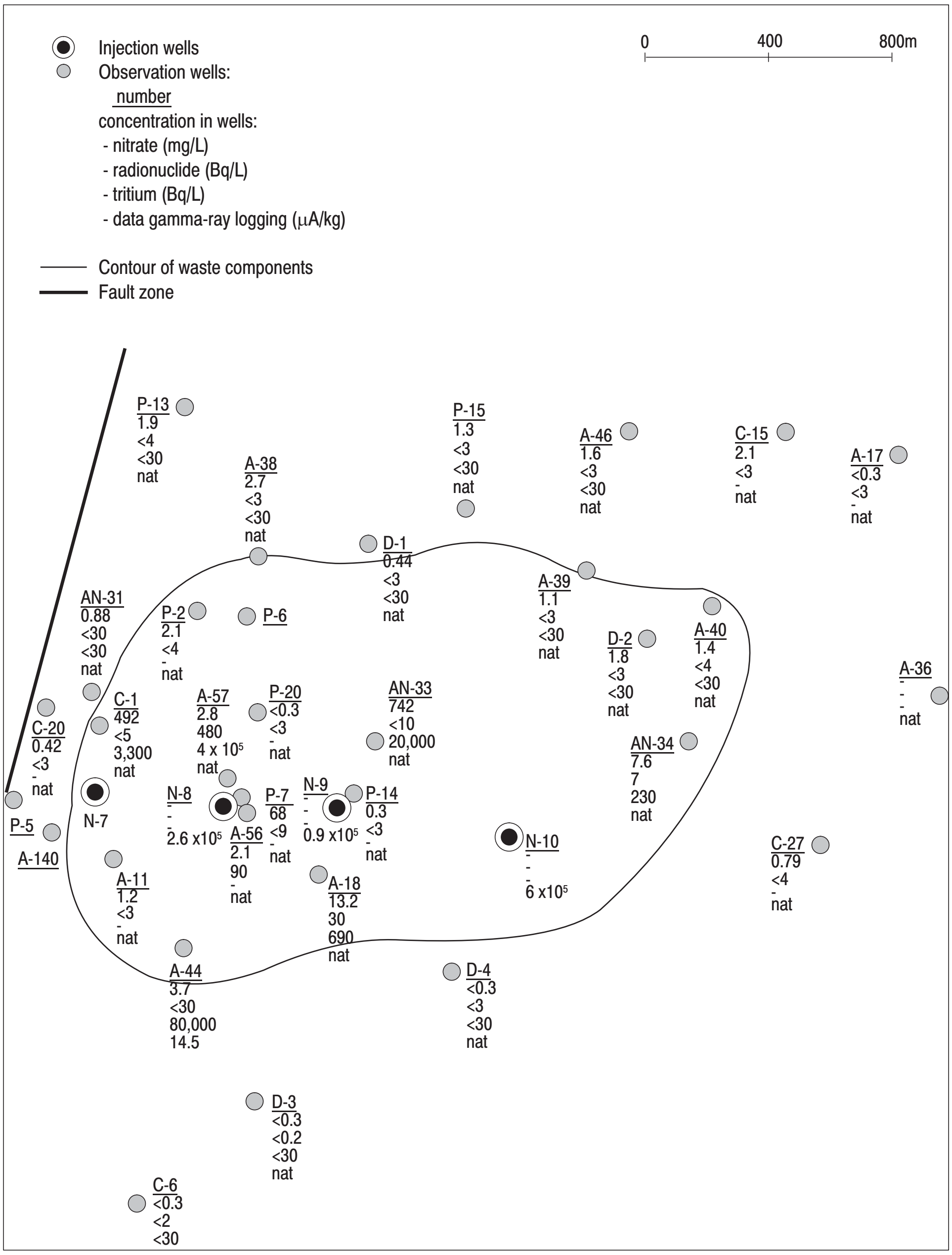

Figure 2.14b. Results from monitoring wells in Horizon II.

The data gathered by the monitoring network include:

- Chemical and radiochemical analyses of waste composition.
- Hydrogeochemical and radiochemical analyses of subsurface waters.
- Hydrodynamic analyses of subsurface heads.
- Geophysical observations of physical fields, including gamma logging, beta logging, thermal logging, resistivity logging, and flowmeter logging.
- Radiological analyses of atmospheric, surface water, soil, and vegetation samples.

Monitoring Results

Table 2.11 indicates the results of sampling carried out in observation wells in Horizons I and II. The locations of these wells are shown in *Figure 2.7*, and the monitoring results are shown in *Figure 2.14*.

Seismic Monitoring

Concerns about induced seismicity prompted the installation of a seismic monitoring facility. The system, an ISMPR-1 seismic station, was designed by the RAS Institute of Lithospheric Physics, and comprises a central station and 12 peripheral measurement stations with KAGK-D-1 and POISK apparatus, as shown in *Figure 2.15*.

Up to three components of the seismic field are logged at each station, covering an augmented frequency band, and signals are transmitted by cable to the central station in digital and analog form. No signs of induced seismicity have been noted, although seismic events associated with distant earthquakes have been noted several times.

The system also includes a geodetic leveling system to detect changes in the ground surface as a result of operation of the injection wells. Vertical displacements of the surface, characteristic of calm platform areas, range between 1–2 mm/yr. Changes have been noted at the surface near the injection contour when Horizon II wells are operating. These changes are near the detection limit of the system. No changes associated with operation of Horizon I injection wells have been reported.

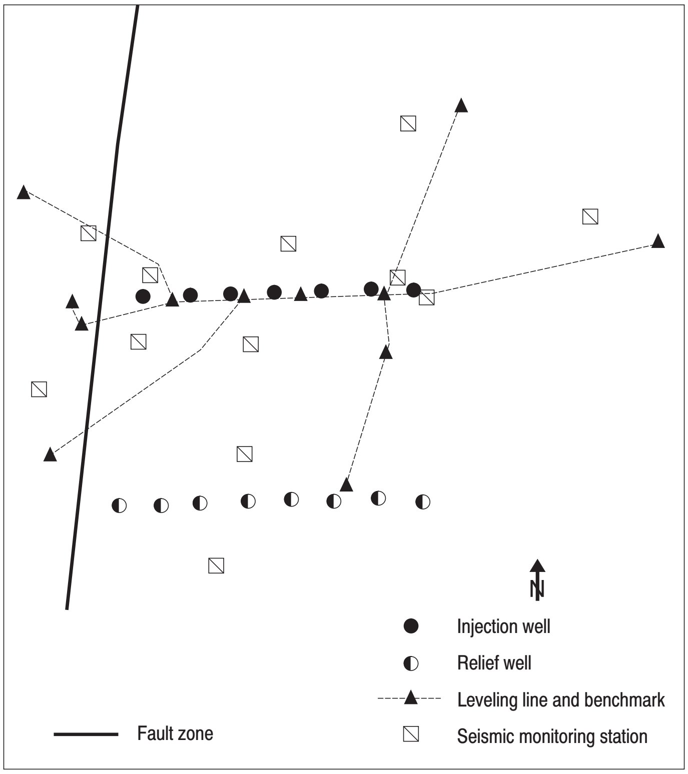

Figure 2.15. Seismic monitoring at the Severny site (Rybalchenko *et al.*, 1994).

3

General Overview of Results

The following chapter reviews the results obtained by the three research groups on modeling the migration of wastes in Horizon I and Horizon II under the normal evolution scenario. Modeling efforts focused primarily on the area within the exclusion zone. Data for all of the groups was provided by the All-Russia Research and Design Institute of Production Engineering (VNIPIPT) and the Mining and Chemical Combine (MCC) at Zheleznogorsk.

3.1 Description of Analysis Scenarios

The base case assumptions were used to estimate the impact of radioactive waste (RW) disposal under current best estimates of environmental conditions and waste inventories. As such, it is not the most conservative estimate of risk. However, the estimate provides the basis for a sensitivity analysis, which can be used to determine the likelihood of situations leading to a violation of regulations or to the creation of unacceptable risks to current and future generations. The base case included the following assumptions:

- The fault zone is essentially impermeable and prevents groundwater flow to the west.
- The aquifers are vertically homogeneous and are characterized by lateral heterogeneity of thickness and transmissivity as reflected in the data provided by VNIPIPT (1998).
- All of the analyses conducted used the assumption of a nonreactive, nondecaying contaminant as a conservative estimate of plume movement.

Some assumptions were varied as a part of the base case. There are therefore two major variants of the base case:

- The waste density affects the migration of the wastes in the subsurface, causing contamination plume migration to deviate from the regional flow patterns.
- The effects of waste density are negligible, and, therefore, contaminant migration follows regional groundwater flow patterns.

In addition, the role of the confining layer between Horizons I and II is in question. None of the groups constructed a full three-dimensional model of all strata present at the site; rather, each horizon was modeled separately, with different boundary conditions. In the International Institute for Applied Systems Analysis (IIASA) and VNIPIPT analyses, groundwater flow and contaminant transport in horizons were described with single-layer, two-dimensional (areal) models. The VNIPIPT analysis assumed a no-flux boundary at every point in the interior of the model, and only applied constant head boundaries on the edges of the modeling domain, where appropriate. The IIASA analysis applied a constant head boundary in the valley of the Bolshoi Tel in order to determine the magnitude of potential vertical leakage. The observed head in the region of the Bolshoi Tel was held constant, and a determination of the inflow or outflow in each model cell required to obtain this observed head was then obtained from the model. In the analysis of the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (IGEM) of the Russian Academy of Sciences (RAS), a multi-layer two-dimensional model was employed for the aquifer under study, with a term reflecting hydraulic interaction between Horizons I and II (in the analysis of migration in Horizon I) and between Horizons I, II, and III (for the analysis of migration in Horizon II). The head of the overlying aquifer (and underlying aquifer, for the analysis in Horizon II) was held constant to determine a conjugated transmissivity/leakage distribution.

Several hypothetical scenarios of accidents and waste migration were discussed, although these were not analyzed in the current report. A discussion of hypothetical accidents and problem scenarios is provided in the report of VNIPIPT (1998). These scenarios are planned for analysis in the second phase, and will be addressed in a separate report on hypothetical and accidental scenarios.

3.2 Comparative Analysis of Modeling Approaches

3.2.1 VNIPIPT

As VNIPIPT has conducted ongoing analyses of the potential for migration at the site, the primary purpose of the modeling at VNIPIPT was to verify the suitability of the data presented to IGEM and IIASA. In addition to the other tasks of VNIPIPT, they carried out several analytical items for this study. The first analysis used the code MT3D in conjunction with MODFLOW to estimate contaminant migration in Horizon I and in Horizon II. The analysis assumed a vertically homogeneous, nonleaky confined aquifer. The exclusion zone was taken as the boundary of the modeling domain, and modeling was projected for 1,000 years in Horizon I and 300 years in Horizon II, in accordance with the requirements of applicable Russian laws and standards. The modeling was carried out for a nondecaying, nonsorbing contaminant. A dispersive model was applied, with values of the longitudinal dispersivity α_L = 1.0 m, the transverse dispersivity α_T = 0.1 m, and the vertical dispersivity α_V = 0.05 m. The second item was the presentation of an analysis that includes the effects of density-driven transport carried out using internal Russian codes (Okunkov *et al*., 1994). The third analysis was an evaluation of possible failure modes and emergency situations. This analysis comprised a description of possible failures and emergency situations, including discussion and analysis of the causes and consequences for some of the emergency situations. This final analysis will be discussed in more detail in the report on hypothetical and accidental scenarios.

3.2.2 IGEM

IGEM conducted four studies. The first report analyzed the impact of different driving forces on the movement of a high-level RW plume in an inclined aquifer. The second report was an analysis of the data presented by VNIPIPT on areal distributions of hydraulic head and transmissivity values in Horizon I; the study's objective was to estimate the internal consistency of the two values. The third report included results of recalibration of transmissivity distribution and modeling of plume migration in Horizon I. The final report was a recalibration of the transmissivity distribution and model of plume migration in Horizon II.

The first report (IGEM, 1997) was a comparative study of thermal, density, and regional flow driving forces exerting influence on the movement of a high-level RW plume in a sloping aquifer. In order to analyze the role of these forces, a simplified representation of Horizon I was developed that consists of a sloping aquifer of infinite lateral extent and bounded at the top and bottom by planar surfaces. The initial plume body was assumed to be cylindrical. A representation of the idealized aquifer with the plume body at the initial moment is shown in *Figure 3.1*.

In this simplified representation, it was found that for high-level wastes (HLWs), modeling of the plume movement within approximately the first 100 years requires accounting for the coupling of all three driving mechanisms, i.e, thermal, density-driven, and regional convection. However, the heat generation rate of the HLWs decays rapidly with time. Hence, for long-term predictions, an influence of the thermal convection is not essential, and it is sufficient to limit analysis by taking into account only driving forces caused by regional flow and heterogeneous distribution of solute concentration. The movement of non–high-level wastes can be described satisfactorily by considering only the effects of regional and density-driven flow. For low-level wastes (LLWs), density effects dominate thermal effects.

The second report, delivered by IGEM (1998a) in February 1998, was a digital representation and preliminary analysis of the data on properties of Horizon I presented by VNIPIPT in a graphic form. Qualitative analysis of the hydraulic head contours for Horizon I at the northern boundary of the exclusion zone (close to the

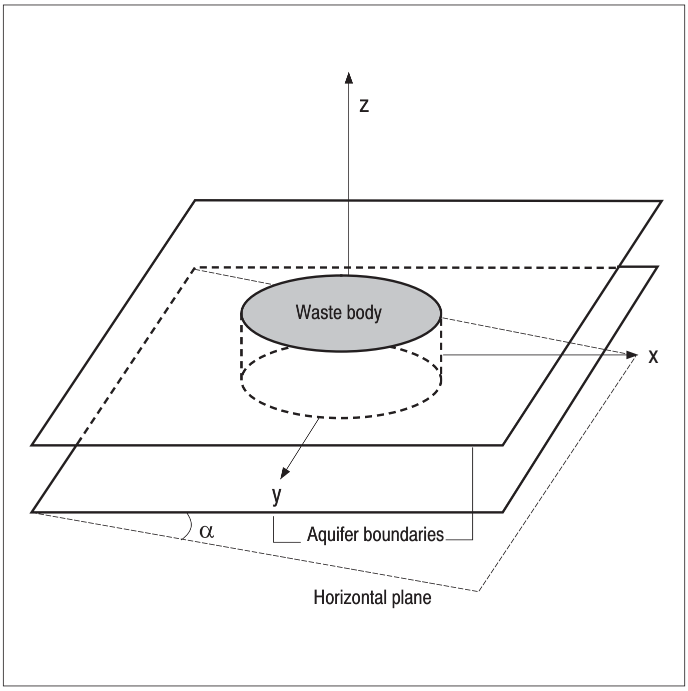

Figure 3.1. Initial representation of the plume body.

Bolshoi Tel River; see IGEM Report, 1998a, Figure 2-6) showed that conditions of water balance for Horizon I could be satisfied only if a leakage through the clay layer between Horizons I and II was taken into account. This assumption was confirmed by quantitative analysis of the water balance in the aquifer that called for recalibration of the input data for predictive simulation.

The third report, delivered by IGEM (1998b) in May 1998, included a solution of the calibration problem, i.e., determination of the distributions of transmissivity values in Horizon I and hydraulic resistance of the clay layer between Horizons I and II, which is consistent with the data actually obtained from pumping tests on transmissivity values in Horizon I and measurements of hydraulic heads in the Horizons I and II (see *Table 2.2*). The data obtained from the calibration procedure were then used in modeling contaminant plume movement in Horizon I, with consideration for density effects. Two methods were used for this modeling. In the first, the code HST3D was used for three-dimensional modeling. In the second, a site-specific finite-difference algorithm was developed. The results presented here are the results of the site-specific finite-difference model. Details of the results of modeling with HST3D, and a comparison of the results of HST3D and the original model, can be found in their report.

The final IGEM analysis (IGEM, 1999a, 1999b) was an analysis of waste migration in Horizon II. The transmissivity and leakage distributions were developed in a manner similar to that used for Horizon I. The computer code JDB-MOC (GeoChem Software, Inc., 1995) was used to model waste migration for a period of 100 years.

3.2.3 IIASA

The analysis conducted by IIASA consists of three elements. The first was a simple screening analysis of the waste inventories to determine the amount of time required for wastes to decay to safe levels and the associated degree of sorption required to ensure retention within the site boundaries for that period. The second was a more detailed analysis of groundwater movement in Horizons I and II. The last was a screening analysis of the potential for contamination of the Bolshoi Tel due to discharges from the aquifers.

The screening analysis of the waste inventories was conducted by estimating the time required for wastes to decay to DC_B levels, assuming that that there would be no concentration or dilution mechanisms. Since there would be some dilution due to advective dispersion, this is expected to be a conservative estimate of the required holdup time. A simple analytical calculation of the travel time to the site boundary was conducted and used to estimate the required degree of holdup. This calculation then allows an evaluation of the degree of sorption required to retain waste components within the exclusion zone boundary for a time sufficient to allow radioactive decay to reduce concentrations below Russian water standards.

The second analysis was an evaluation of groundwater movement in each aquifer. The code MOC3D in conjunction with MODFLOW was used to estimate the travel time of groundwater from the area of the contaminated plume to the site boundaries. Each horizon was modeled separately. A single-layer, two-dimensional model of each horizon was developed and used to estimate the time for migration of groundwater from the disposal area to the site boundary. No decay or retardation was assumed; as in the VNIPIPT and IGEM analyses, a nonsorbing and nondecaying generic "tracer" was modeled. In addition, no dispersivity was taken into account. As there are measurements of the distribution of nitrates in each aquifer, the measured concentrations of nitrate were used to generate an initial plume for modeling. The initial plume for modeling was developed by interpolating values for concentration, and truncating the obtained distribution to obtain a plume similar in extent to that reported in the data of VNIPIPT. The boundary of the plume is thus defined in all IIASA figures at 1 g/L in Horizon I, and 0.05 g/L in

Horizon II.[1] Therefore, unlike the VNIPIPT and IGEM analyses, the initial plume is not uniform in concentration; rather, it is distributed within the disposal areas, with the highest concentrations near the injection wells.

The final analysis was a conservative estimate of the discharge of contaminated groundwater to the Bolshoi Tel. The output of MOC3D was used to determine the rate of contaminant loss due to discharge from the aquifer. This was calculated as a percentage flux, and then scaled by the amount of each nuclide initially present. This flux was then corrected to account for radioactive decay during the travel time. This flux was then assumed to be advected instantaneously to the river, entering the river as a point source and immediately mixing with the river water. The minimum reported water flow for the Bolshoi Tel was used to determine the level of dilution due to mixing of the contaminated groundwater with the river water.

3.3 Modeling Results

3.3.1 Horizon I

The first variant of the base case involved modeling groundwater flow in the absence of density-driven flow effects. This case was modeled by VNIPIPT and IIASA. *Figure 3.2* shows the results of plume movement.

Figure 3.2a shows the concentration of the plume in relative units, where the initial plume was defined as having an initial concentration of 1 unit. *Figure 3.2b* shows the extent of the plume at different times, as defined by the 1 g/L nitrate isoline.

Although there are slight differences between the two plots, the basic features are similar. Both show plume migration to the north-northeast of the disposal ground, and both show that the plume does not contact the allotment boundary within the 1,000-year limit. The IIASA analysis is continued past the 1,000-year limit, showing a contact with the allotment boundary between 1,000 and 1,500 years.

The second variant of the base case was modeled by IGEM and VNIPIPT to determine the effects of density differences between the waste and groundwater. The IGEM analysis was carried out taking into account the effects of density-driven flow and leakage through the layer between Horizons I and II, and used a recalibrated distribution of transmissivity in Horizon I. The results of this modeling

[1]For purposes of comparison, the injected concentration of HLW contains 120–360 g/L of nitrates, and intermediate-level waste (ILW) contains between 100–150 g/L. LLW contains approximately 4–20 g/L. The extent of the plume as defined is therefore approximately 0.25–1.0% of the initial injected concentration.

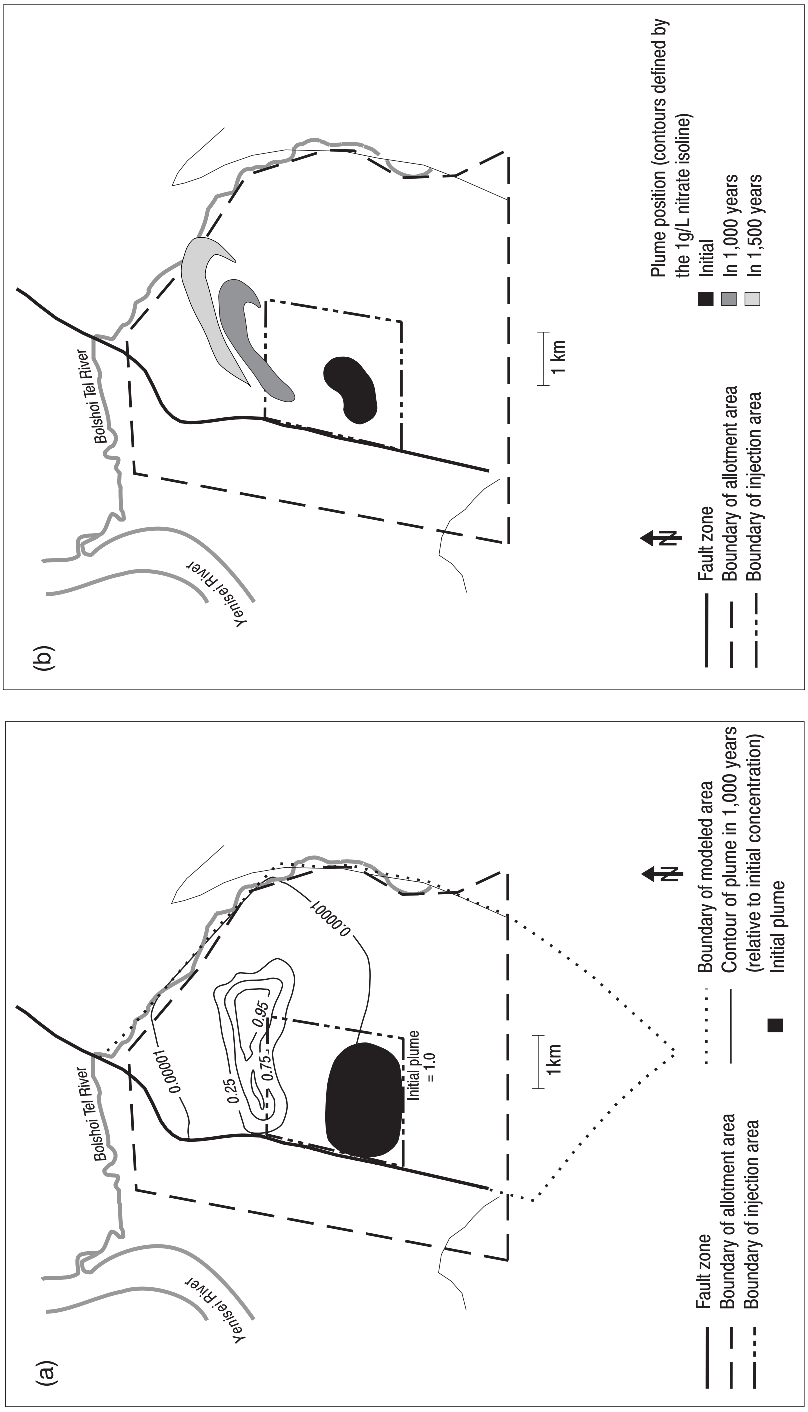

Figure 3.2. Horizon I transport results: (a) VNIPIPT and (b) IIASA.

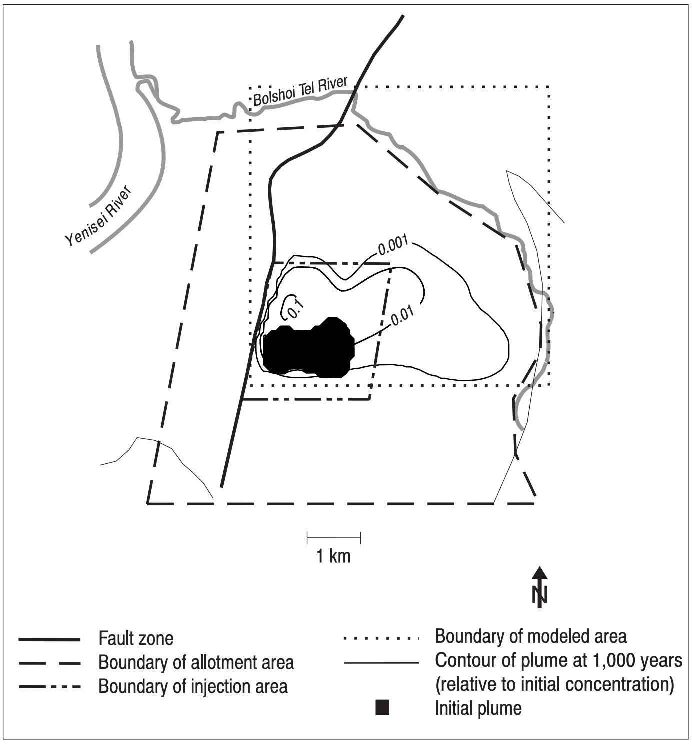

Figure 3.3. IGEM analysis of density-driven plume migration in Horizon I.

effort are shown in *Figure 3.3*. As in the VNIPIPT analysis, the initially contaminated area was assigned a relative concentration of 1 unit. The isolines are relative to the 1 unit of initial concentration.

Three-dimensional modeling, through the use of HST3D, confirms this character of contaminant plume movement. As would be expected, these results differ from those obtained when modeling neglects the effects of density-driven flow and leakage through the upper boundary of Horizon I. Gravity forces tend to move the plume to the north and settle into the depression north of the injection zone rather than moving northeasterly, following the pattern of regional groundwater flow. A small portion of the more diluted (and, hence, less dense) wastes moves to the east under the influence of the regional flow. Therefore, modeling with consideration for the density effects shows that they cause the bulk of the plume to be trapped in the synclinal region. This general character of density-driven flow is confirmed in the results presented by VNIPIPT, in which waste migration of dense wastes at 650 years is shown (see *Figure 3.4*).

In order to provide a consistent comparison, *Figure 3.5* shows the results of all three groups, plotted on the same scale. It was necessary to make assumptions

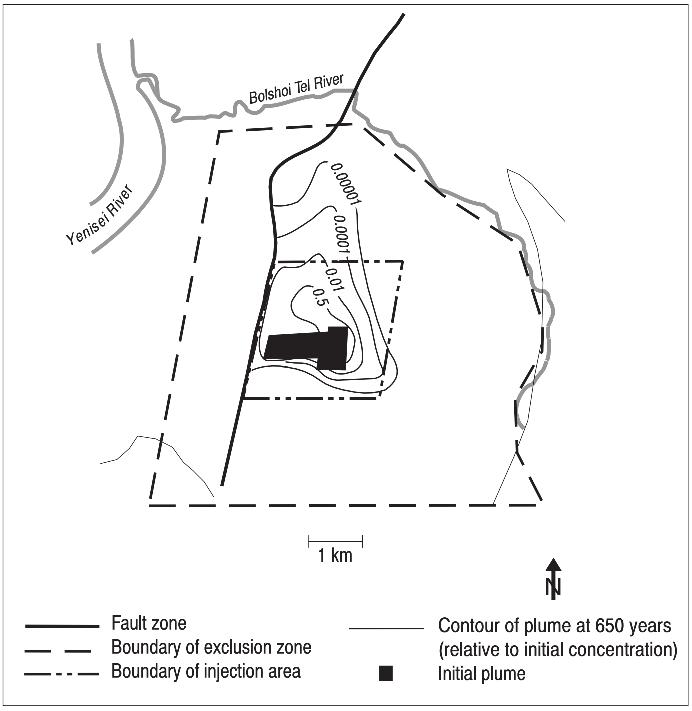

Figure 3.4. VNIPIPT analysis of density-driven plume migration in Horizon I over 650 years (adapted from Okunkov *et al.*, 1994).

about the extent of the plume in order to define the plume in a comparable way for each plot. For the VNIPIPT and IGEM results, the boundary of the plume was shown for a relative concentration of approximately 10–30% (relative to a uniform initial groundwater concentration of 100%). For the plots of the IIASA results, the boundary of the plume is the 1 g/L isoline, which is approximately 1% of the initial injected concentration. The results of migration at 1,000 years in Horizon I are presented (with the exception of the VNIPIPT assessment of dense wastes, for which a projection of only 650 years was carried out).

The results are quite similar. None of the analyses indicate the migration of the groundwater beyond the allotment area within 1,000 years. Modeling of the flow in the absence of density effects shows the plume moving to the north-northeast, and migrating well over half of the distance to the river. Modeling of a dense plume, on the other hand, shows that the majority of the plume migrates to the north, and settles into the depression slightly north of the site. It is important to note that the plume is composed of miscible fluids. Therefore, not all of the radionuclides will

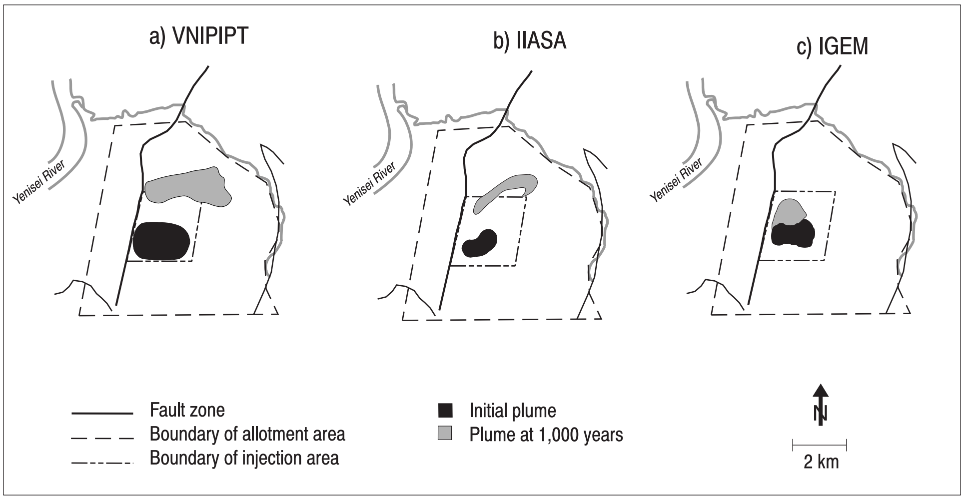

Figure 3.5. Summary comparison of results for Horizon I over 1,000 years.

be trapped in the depression indefinitely. An accurate picture of the migration of the wastes will therefore lie somewhere between these two projections.

3.3.2 Horizon II

Since the wastes are much less concentrated in Horizon II, there is no need to account for density differences when modeling waste transport in this aquifer. The results of all three modeling efforts demonstrate plume movement to the north-northeast toward the middle reaches of the Bolshoi Tel. The rate of plume migration is much faster in Horizon II than in Horizon I, with the plume arriving at the boundary of the allotment area in 150–300 years. The results of the analyses of VNIPIPT and IGEM are shown in *Figures 3.6* and *3.7*.

The VNIPIPT plot shows the wastes, relative to an initial waste concentration of 1 unit, at 300 years. It can be seen that the wastes have already contacted the allotment boundary within 300 years. In the IGEM analysis, the position of the plume at 100 years was simulated, starting from an initial concentration of 100 units. Although the IGEM analysis was not projected past 100 years, it indicates a groundwater velocity of approximately 15 m/yr. This would lead to a contact of the plume with the allotment boundary in approximately 200–250 years.

The IIASA analysis was for a 500-year period, and shows the time required for discharge of the plume to the Bolshoi Tel. As the concentrations of waste indicators are much lower in Horizon II, a limit of 0.05 g/L was used to define the initial plume, based on the interpolation of monitoring results for nitrates in Horizon II. The plume as shown on the plot also shows the limit of the plume as defined by the

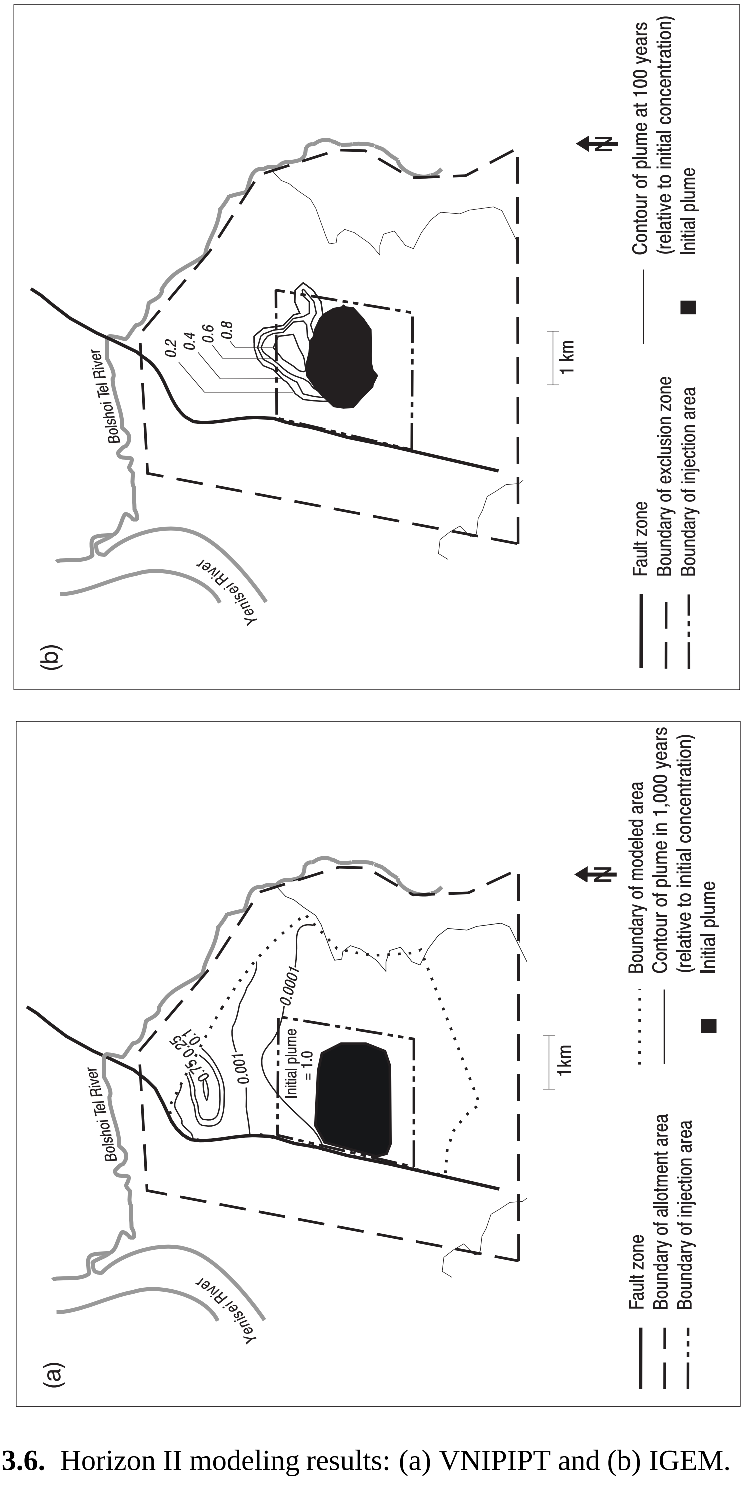

Figure 3.6. Horizon II modeling results: (a) VNIPIPT and (b) IGEM.

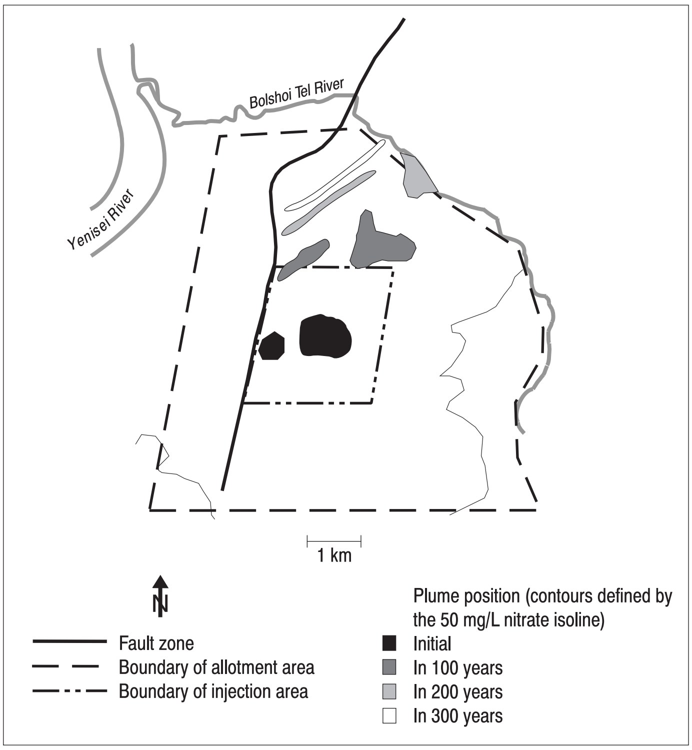

Figure 3.7. Horizon II modeling results: IIASA.

0.05 g/L isoline. The plume contacts the allotment boundary in 150–200 years, and only the tail of the plume remains south of the Bolshoi Tel after 300 years.

In order to provide a consistent comparison, *Figure 3.8* shows the results of all three groups, plotted on the same scale. It was necessary to make assumptions about the extent of the plume in order to define the plume in a comparable way for each plot. For the VNIPIPT and IGEM results, the boundary of the plume was shown for a relative concentration of approximately 10–30% (relative to a uniform initial groundwater concentration of 100%). For the plots of the IIASA results, the boundary of the plume is the 0.05 g/L isoline, which is approximately 1% of the initial injected concentration. Unfortunately, the different groups presented results for different periods. The IGEM analysis shows results for migration of the plume at 100 years, and this is therefore comparable with the IIASA results at 100 years. The VNIPIPT results were presented for 300 years, and are therefore comparable with IIASA results at 300 years. In addition, the modeling extent of the VNIPIPT analysis appears to fall short of the exclusion zone boundary, which indicated that the plume shown in the figure is truncated, and in fact extends further to the north.

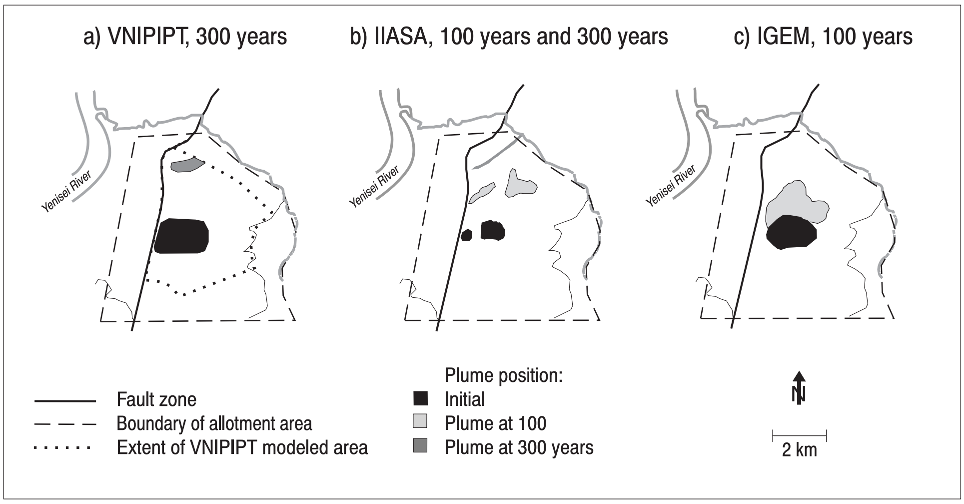

Figure 3.8. Summary comparison of results for Horizon II.

Although the figures are somewhat less comparable, some conclusions can still be drawn. The rate of waste migration in Horizon II is much faster. The IIASA analysis appears to shows the fastest rate of groundwater movement, resulting in the shortest travel time to the boundary of the exclusion zone. However, the results are in agreement with IGEM results to within a factor of two, indicating that contact of the nonsorbed plume with the boundary of the exclusion zone will occur sometime in 150–250 years. Because of the truncation of the VNIPIPT results, it is somewhat difficult to interpret the time of contact with the exclusion zone boundary. However, it appears that the results are roughly consistent with the results obtained by IIASA, therefore lending a degree of support to the hypothesis that the nonsorbed plume will contact the site boundary in the 150–250-year timeframe.

3.3.3 Analysis of required sorption

Due to uncertainties regarding the interaction between the waste and the host rock, a simple scoping analysis was performed to estimate the degree of sorption required to ensure that radioactive decay would reduce concentrations at the allotment boundary to applicable Russian drinking water standards, as codified in NRB-96. It is important to note that this is not an analysis of the actual level of sorption; this is an analysis of the distribution coefficient required to ensure sufficient holdup time for concentrations to decrease to drinking water standards. These required distribution coefficients are then compared to reported values of K_D (distribution coefficient) for these nuclides. If the required distribution coefficient is much lower than reported values, it is an indication that the holdup time will be much longer than that required; if the required distribution coefficient is in the range of reported distribution coefficients, or is higher than reported coefficients, it indicates that sorption alone may not prevent unacceptable concentrations of these nuclides at the allotment boundary. The analytical model indicated a groundwater travel time of 1,000 years for Horizon I and 220 years for Horizon II. Assuming a porosity of 0.07 for Horizon I and 0.1 for Horizon II, the following distribution coefficients were determined:

Distribution coefficients required to prevent migration outside allotment zone (cm^3/g).

Nuclide	LLW	ILW	HLW
^{241}Am			0
^{135}Cs		340	360
^{137}Cs	0	0	0
^{237}Np			730
^{239}Pu	18	13	13
^{90}Sr	0	0	0
^{99}Tc		58	58

If we compare these values with the estimated values for K_D given previously, we see that the only nuclide requiring any retention whatsoever in the LLW of Horizon II is ^{239}Pu. Since the minimum reported K_D for this nuclide is 110 cm^3/g, it appears that sorption will be sufficient to prevent ^{239}Pu migration outside of the allotment boundaries in Horizon II. In Horizon I, it can also be seen that even low levels of sorption will retain ^{239}Pu within allotment boundaries until radioactive decay has reduced groundwater concentrations. Although *Table 2.6* gives a value of 1.4–1.6 cm^3/g for ^{239}Pu, this is only under highly acidic conditions. Neutralization of the wastes over time may result in distribution coefficients rising to the values similar to those reported for ILW or LLW. Certainly, any plutonium escaping the disposal ground will have to traverse a region of the aquifer where the waters are essentially fresh, and where the pH is not acidic.

However, it appears that there are some nuclides in Horizon I with the potential to escape the allotment zone with groundwater concentrations above drinking water levels. ^{99}Tc and ^{237}Np are not likely to have distribution coefficients above 58 cm^3/g or 730 cm^3/g, respectively. In addition, if it is assumed that ^{135}Cs is characterized by a distribution coefficient similar to ^{137}Cs, then it can be seen that the values of 340–360 cm^3/g are much higher than those given previously for ^{137}Cs, even for LLW. However, concern regarding these nuclides (^{99}Tc, ^{237}Np, and ^{135}Cs) should be tempered by the recognition that they are present in initial concentrations only one to two orders of magnitude greater than allowable levels. In addition, considerable additional travel time is required for any vertical migration of wastes to the surface, which was not reflected in this conservative analysis. Finally, this analysis assumes an instantaneous and reversible partitioning between the solid and liquid phases. Radiochemical analyses presented in Rybalchenko *et al.* (1994) indicate that the potential desorption is less than 100%, which would indicate that use of the instantaneous reversible partitioning model adds a level of conservatism. Therefore, lower initial partition coefficients between waste and the soil matrix than calculated in this simple screening analysis may be sufficient to ensure permissible drinking water concentrations at the allotment boundary. However, more detailed analyses would be required to substantiate this.

3.3.4 Discharge to the Bolshoi Tel

In addition to these studies of subsurface migration, IIASA conducted a scoping analysis to evaluate the significance of potential discharge of wastes to the Bolshoi Tel. The analysis was conducted in a conservative manner, assuming that all wastes reaching the boundary of the allotment zone, a distance of approximately 4 km, migrate instantaneously and vertically upward to the Bolshoi Tel. There, the wastes are mixed with the average minimum annual flow of the Bolshoi Tel, determined to be approximately 27 million m^3 per year (corresponding to 0.9 m^3/sec). The rate of discharge was calculated by determining the rate of mass lost from the aquifer (by determining the total mass lost in a time step divided by the time step; that is, $\Delta M/\Delta t$, where Δt is 50 years in Horizon II and 500 years in Horizon I), and assuming that all of this mass was lost due to vertical discharge to the Bolshoi Tel. The only factor that may increase the maximum concentrations would be a finer resolution of the peak of the distribution with a smaller time increment. Sorption was considered by increasing the estimated travel time of the nuclides by their associated retardation factor. Radioactive decay during this period was also applied, resulting in a reduction of the inventory escaping the subsurface boundary of the exclusion zone. The conservatism in the analysis consists of two elements. For HLWs, it assumes that the retardation factor of the acidic wastes does not change, but stays at very low values. In addition, vertical travel time is neglected, whereas the actual vertical travel time through the confining layer between Horizon I and Horizon II is expected to be on the order of tens of thousands of years. The IGEM estimate of groundwater travel time through the confining layer, based on the hydraulic conductivity, thickness, and head difference between Horizon I and Horizon II, is shown in *Figure 3.9*.

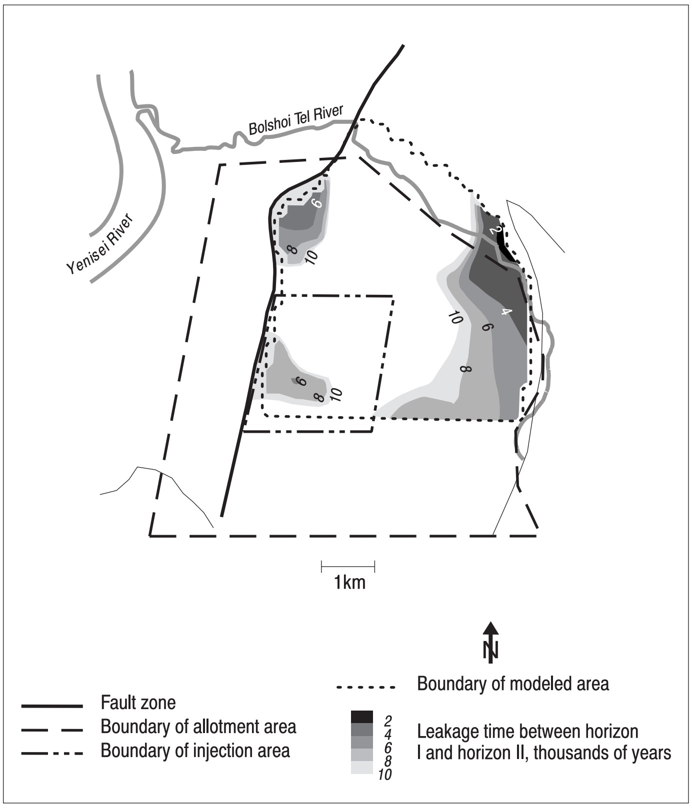

Figure 3.9. IGEM estimate of groundwater travel time from Horizon I to Horizon II.

It can be seen in *Figure 3.9* that the travel time through the confining layer is much longer than the travel time to the boundary of the allotment area. If the effects of sorption are included, these times will increase. As the wastes in Horizon I must traverse the confining layer prior to discharge into the Bolshoi Tel, the actual travel times of contaminants from the subsurface disposal zone in Horizon I to the Bolshoi Tel River may be far larger than 1,000 years. This analysis is thus a conservative estimate of the concentration in the river water. Only if significant undetected fractures connecting Horizon I, Horizon II, and the surface are present will the estimates of vertical migration time be significantly in error. As the analysis does not take credit for vertical travel time, the presence of fractures linking the aquifers and the Bolshoi Tel will not affect these estimates. The results of this analysis are presented in the following:

Maximum doses in the Bolshoi Tel River, mSv/yr.

Nuclide	LLW	ILW	HLW
^{241}Am			1.1×10^{-6}
^{135}Cs		7.4×10^{-4}	2.9×10^{-5}
^{137}Cs	0	0	0
^{237}Np			8.2×10^{-4}
^{239}Pu	4.9×10^{-7}	2.4×10^{-4}	1.5×10^{-2}
^{90}Sr	0	0	0
^{99}Tc		7.6×10^{-3}	2.4×10^{-4}

Even under these assumptions, it can be seen that the annual doses from radionuclides are several orders of magnitude below the current 1 mSv annual dose limit. ^{239}Pu, due to its long half life, shows a safety factor of 66. In reality, the extremely low retardation factor used in this analysis, characteristic of acidic, salty HLW, is likely to be much higher, and the margin of safety is therefore likely to be much higher. Of concern due to its high mobility (and therefore minimal time for radioactive decay), ^{99}Tc presents the next lowest margin of safety, and even so is still more than 100 times below the allowable dose. It therefore appears unlikely that nuclides from the disposal areas will lead to contamination of the Bolshoi Tel at levels that would result in exceedance of the 1 mSv annual dose limit, even if such vertical discharges do occur.

Based upon these analyses, there are two areas in which further studies would clarify the situation.

- Analysis of the potential, within both Horizon I and Horizon II, for high-permeability layers that could lead to decreased groundwater travel times to the site boundaries.
- A reassessment of potential vertical interconnections between the two aquifers and the potential of the discharge of Horizon I groundwaters to the Bolshoi Tel, particularly in the northeastern region of the exclusion zone. Such an analysis would support decommissioning of the disposal site by providing better data for the design of monitoring programs.

Short-term risks would be best addressed by the first proposal, since high permeability zones in Horizon II, if present, could result in surface contamination within a relatively short period, on the order of magnitude of a hundred years. Long-term risks are best addressed by the second proposal, as the hypothetical discharge of Horizon I in this region, even if it does occur, is not expected to result in any introduction of Horizon I wastes into the Bolshoi Tel for at least the next several thousand years.

4

Conclusions and Recommendations

It appears that all three groups reached similar results where similar modeling assumptions were used. For Horizon I, none of the analyses showed plumes migrating beyond the site boundary within 1,000 years. Since the majority of the activity in the repository is characterized by intermediate or short half-lives, most of the activity will decay to Russian drinking water standards within the 1,000-year limit. Density-driven flow, modeled by the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (IGEM) and the All-Russia Research and Design Institute of Production Engineering (VNIPIPT), has the effect of causing a more northerly flow, and results in a trapping of the majority of the dense wastes in the depression north of the site. The flow in Horizon II is much faster than in Horizon I, but will require approximately 100-300 years for the groundwater to contact the site boundary, and the much lower concentration of radionuclides results in similarly low concentrations of radioactive contaminants at the site boundary.

These results indicate that the assertions of groundwater velocities of 250 m/yr in Horizon I and 350 m/yr in Horizon II (as cited in Robinson and Volosov, 1996) are not consistent with the hydrogeological data gathered over the past 30 years. If these values were correct, constituents of the waste injected in the late 1960s and early 1970s would have already reached the site boundaries. There is no evidence that this has occurred. It can only be surmised that these values reflect groundwater velocities in the vicinity of the injection wells during site injection. However, under normal subsurface conditions, groundwater velocities are much lower than those reported in the Green Cross report, being no more than approximately 5 m/yr in Horizon I and 20 m/yr in Horizon II.

As a conservative measure, none of the migration analyses explicitly modeled sorption in estimating contaminant travel time. The results of the International Institute for Applied Systems Analysis (IIASA) screening analysis indicate that even very low levels of sorption will be sufficient to prevent unacceptable levels of wastes at the site boundary.

Two studies addressed the issue of discharge of contaminated water to the Bolshoi Tel. Section 3 of the IIASA analysis, assuming instantaneous vertical transport from the aquifers to the river, indicates that the low rate of discharge would be substantially diluted with the flowing river water. This result is complemented by the results of the IGEM (1998b) analysis, which indicates that even if such discharge should occur, the travel time through the intervening layers is likely to be approximately thousands of years. The combined effects of dilution and radioactive decay during migration to the accessible environment are likely to provide a large margin of safety for the Bolshoi Tel.

Based on the preceding analyses and results, several conclusions can be drawn and recommendations made for further activity.

1. *A hydraulic connection between the deep aquifer (Horizon I) and the intermediate aquifer (Horizon II) is consistent with observed geohydrological data and may result in migration of some portion of the wastes from the deep aquifer to the shallower aquifer. However, under current conditions, the travel time for this pathway is likely to be thousands to tens of thousands of years due to the properties of the intervening confining layer. Thus, the radiological impacts are unlikely to be of concern because most of the injected nuclides are relatively short-lived.*

Discharge of the injected wastes to surface waters has been a persistent theme in questions raised regarding the safety of the repository. One of the key geological factors in selecting this repository site was the assumed presence of a confining layer of low permeability separating Horizon I and Horizon II throughout the subsurface exclusion zone. This hypothesis was examined by site studies of the permeability of the confining layer in the northeastern section of the site, near the Bolshoi Tel, which indicate that the conductivity between the layers is very small. However, IGEM (1998a, 1998b) analyses of geohydrological data indicate that there may be a hydraulically significant connection between the two aquifers. In addition, results of the IIASA (1998) analysis indicated that reproduction of the observed head distribution was difficult to achieve unless the assumption of a discharge of Horizon I to Bolshoi Tel River rather than the Kan River was made. These results indicate that there is some question regarding the potential for vertical leakage and interconnection of the two aquifers within the area of the exclusion zone. However, based on results of the IGEM analysis, it appears that the magnitude of the connection between the aquifers, although significant in determining the subsurface hydrology (particularly that of Horizon I), may be relatively minor in terms of the ability to introduce significant amounts of contamination to the upper aquifer (IGEM, 1998b). The properties of these less-permeable strata appear to result in extremely long travel times of groundwaters between the two aquifers. Since only a small fraction of the waste injected into Horizon I is long-lived, the potential for significant contamination of the upper aquifer appears low. Nevertheless, further studies could be carried out to provide a more precise determination of the properties of the intervening strata, particularly in the region of the Bolshoi Tel, and to analyze the impact of permeability of these confining layers.

2. *After only 100–200 years, the effects of thermally driven flow are likely to be negligible in comparison to regional and density-driven flow in the modeling of ILW/HLW migration in Horizon I. The density-driven flow causes the dense portion of the contaminant plume to move in a more northerly direction toward the synclinal structure, located within the site boundary to the north of the disposal site near the fault zone, rather than the northeasterly direction of regional groundwater flow. This results in the trapping of the dense portion of the contaminant plume within the synclinal structure and therefore minimizes migration of dense wastes further north.*

Analysis of the relative effect of thermally driven, density-driven, and regional flow in Horizon I performed by IGEM (1997), indicates that decay of short-lived radionuclides will result in the elimination of thermally driven flow as a major factor within a period of 100–200 years. However, density effects are likely to persist after this time, and are likely to result in the isolation of a major portion of the dense Horizon I waste liquids in the synclinal depression located along the fault zone due north of the disposal site. Inclusion of density-driven flow will thus result in a difference in the results of plume modeling, yielding a picture of contaminant movement in a northerly direction that slows dramatically when the wastes enter the depression and are trapped there. In the absence of density-driven flow, as modeled in the IIASA (1998) and the VNIPIPT (1998) analyses, both of which considered only regional flow patterns, the plume will move more to the northeast in accordance with regional groundwater flow patterns, and will not be trapped but will continue to migrate with the groundwater. As the migrating waste solutions and groundwaters are miscible, an accurate picture lies somewhere between the two scenarios.

3. *Groundwater travel times appear to be sufficiently long in Horizon I (over a thousand years) to allow for radioactive decay of the short- and medium-lived radioactivity (primarily ^{144}Ce, ^{106}Ru, ^{137}Cs, and ^{90}Sr) to Russian drinking water standards prior to reaching the site boundary. If the effects of sorption are included, this margin of safety becomes considerably larger.*

IIASA (1998) analyses of the initial concentrations of individual radionuclides in the waste indicate that the isolation time required for radioactive decay of all the nuclides present in the wastes with half-lives of less than approximately 30 years to Russian drinking water standards is, at most, 800 years. This will occur even if the effects of plume dispersion and partitioning of the activity between the solid and liquid phases are not taken into account. Since the groundwater travel time to the site boundary at the Bolshoi Tel is over 1,000 years, it is unlikely that subsurface concentrations of these nuclides will ever exceed Russian drinking water standards at the site boundary under the current understanding of geological conditions. Only if there are undiscovered zones of high permeability within the aquifers could unacceptable concentrations of these radionuclides reach the site boundary. Even under these conditions, sorption of nuclides to the host rock may provide a sufficient margin of safety to prevent subsurface concentrations from exceeding Russian drinking water limits. The bulk properties of the aquifer do not appear to result in problems from short-lived contamination. The potential for identification and characterization of potential areas of high horizontal groundwater discharge within the larger Horizon I complex should be studied. If these areas are identified, then more detailed study of the probable locations should be carried out.

4. *The concentration of the long-lived radioactive material (primarily ^{239}Pu, ^{241}Am, ^{237}Np, and ^{99}Tc) in the groundwater in Horizon I near possible areas of discharge to surface water bodies near the site boundary is likely to be, at most, only one to three orders of magnitude greater than permissible levels in drinking water. Similarly, low concentrations can be expected for the shorter-lived nuclides in Horizon II. The very low hypothesized contribution of groundwater discharge to surface water discharge means that dilution of low volumes of contaminated groundwater with high volumes of river water should result in concentrations of discharged radioactivity lower than permissible levels in surface water bodies, even if such discharges do, in fact, occur. Only if this seepage occurs in a surface region where accumulation of discharged radioactivity is possible (e.g., water is removed by evapotranspiration rather than discharge to flowing surface water) is significant contamination of surface features feasible.*

There appear to be two scenarios where subsurface concentrations at the site boundary may exceed drinking water standards. In Horizon I, this may occur after thousands of years as the long-lived activity reaches the site boundary. However, this activity will then have to migrate upwards to the Bolshoi Tel through less permeable layers. Once it reaches the Bolshoi Tel, it will be diluted with the flowing river water (IIASA, 1998). Using a highly conservative scoping assumption of instantaneous advection of contaminated groundwater under the Bolshoi Tel into the river, the maximum annual dose from any nuclide in the Bolshoi Tel would be due to ^{239}Pu, at a level of approximately 1.5×10^{-5}Sv, almost two orders of magnitude below the 1 mSv annual dose limit. This peak would occur at approximately 2,000 years. Sorption of the remaining long-lived radioactive nuclides results in a far lower discharge rate into the Bolshoi Tel, and therefore a far lower concentration in the river water. Therefore, the potential for significant contamination of the Bolshoi Tel by Horizon I wastes appears slight.

Groundwater in Horizon II will reach the Bolshoi Tel in a considerably shorter time span, estimated as less than 300 years. However, the majority of the constituents in Horizon II are expected to be highly sorbed to the host rock. Because of this, contamination of the Bolshoi Tel by sorbing contaminants (such as ^{137}Cs, ^{90}Sr, and ^{239}Pu) is not expected.

However, if the contamination discharges to the surface in areas that are not diluted by river water, but instead is concentrated by evapotranspiration of the seeped groundwater, then surface contamination may be possible. Further studies characterizing the properties of the discharge zone of Horizon II and any potential discharge zones of Horizon I to the Bolshoi Tel would be useful in assessing the potential for contamination of the Bolshoi Tel.

5. *Within the site boundaries, significant bodies of radioactively contaminated groundwater are likely to remain in Horizon II for hundreds of years, and in Horizon I for hundreds to thousands of years. Relatively short-term isolation (less than 300 years) is required for Horizon II, and a proper design of institutional access controls may be sufficient to prevent access. However, post-closure safety of Horizon I requires the assumption that the water of Horizon I will not be accessed by future generations for hundreds to thousands of years, well after the period that institutional controls can be expected to prevent access. Safety features remaining after institutional controls expire include the depth to the wastes (∼400 m), the relatively low yield of the lower aquifer, and the presence of more attractive groundwater resources at shallower depths (Horizons II and III).*

It appears from the data and analyses given in the reports of IGEM, IIASA, and VNIPIPT that the potential for significant problems outside the site boundary is not likely. This is due, in large part, to the slow groundwater velocities and properties of the aquifers, which retain the radionuclides within the site boundary. However, significantly contaminated groundwater may remain in both aquifers for hundreds to thousands of years (IIASA, 1998). Although the concentrations of the very short-lived radionuclides (^{106}Ru and ^{144}Ce) will decay to permissible levels within a matter of decades, large amounts of moderately short-lived radionuclides (^{137}Cs and ^{90}Sr) will remain for hundreds of years in both Horizon I and Horizon II. Long-lived radionuclides will likely remain in the plumes for thousands of years. Inadvertent use of these contaminated groundwaters could result in very high doses to local inhabitants. Therefore, preventing the use of the groundwater within the present site boundaries is necessary to protect the health of future residents of the region. An assessment of the potential for groundwater use within the site and the adequacy of institutional controls is therefore critical to understanding how to prevent public exposure to unacceptable doses of radiation in the future. Such an analysis would require a study of the feasibility of public use of the disposal aquifers, a more detailed assessment of the particular areas where access controls would be necessary, and the amount of time for which controls would be required.

6. *The fault zone running along the western edge of the site appears to play a major role in preventing the movement of contamination westwards and into the Yenisei River. Evidence of this can be seen in the difference in hydraulic heads across the site and in the pattern of groundwater gradients within the downthrown block. However, the potential radiological impacts of a reduction in the effectiveness of the fault zone as a barrier are not clear and should be investigated.*

Several pieces of evidence point toward the effectiveness of the fault zone in minimizing contaminant migration westwards toward the Yenisei River. These are discussed in more detail in Chapter 3, Section 3.1.2, and include the difference in hydraulic heads in wells on either side of the fault zone and the pattern of hydraulic gradients, which generally result in hydraulic head isolines that are perpendicular to the fault zone, indicating no flow across the zone. It does appear that there is a region approximately 3 km north of the injection array where local anomalies in the heads on both sides of the fault zone indicate a flow through the fault zone, from the downthrown block to the upthrown block. The time required to reach this area is on the order of a thousand years. The impact of this potential leakage site is unclear, although it is hypothesized that it would not result in the introduction of significant contamination to the Yenisei River. However, the impact of a failure of the screening ability of the fault zone is unknown. Should this zone fail, perhaps during an earthquake, the patterns of groundwater flow could be considerably altered, with unknown results. Further studies of the geology of the fault zone may assist in understanding potential failure modes, and a consequence analysis of a failure of the fault zone should provide an understanding of what level of failure would be required to pose a significant radiological hazard.

Summary

Based upon the three analyses presented here, the underground deep injection site at the Mining and Chemical Combine (MCC) does not appear to present any major short-term risk of public exposures or of significant contamination of the surface waters given the current understanding of environmental conditions. This is due primarily to the low groundwater velocities, the degree of sorption that may reasonably be expected at the site, and the potential for dilution of the contaminated groundwater with surface water. The most significant long-term risk appears to be the potential for direct use of contaminated groundwaters.

Appendix 1

General Overview of Environmental Conditions at the Mining and Chemical Combine[1]

In the former Soviet Union, the production of weapon grade plutonium was concentrated at three enterprises:

- Industrial Association (IA) Mayak in Ozersk (formerly Chelyabinsk-65), Chelyabinsk Oblast.
- Siberian Chemical Combine (SCC) in Seversk (formerly Tomsk-7), Tomsk Oblast.
- Mining and Chemical Combine (MCC) in Zheleznogorsk (formerly Krasnoyarsk-26), Krasnoyarsk Krai.

All of these enterprises are located on the territory of the Russian Federation.

The process of plutonium extraction from irradiated uranium fuel includes separation of the two metals and their purification from fission products. Metallic plutonium articles are the final products of the plutonium purification process. Nuclear materials production is accompanied by generation of radioactive wastes (RWs), which undergo processing and then are sent for storage, discharged, or disposed. Radioactive wastes are differentiated by their physical form, volume-specific activity level, and origin.

The RWs are divided into liquid, solid, and gaseous wastes. Waste processing solutions, various suspensions, and sludges are considered liquid wastes. According to public health regulations contained in NRB 76/87, OSP 72/87, and SPORO-85, liquid radioactive wastes (LRWs) are classified as low-level ($<10^{-5}$ Ci/L), intermediate-level (from 10^{-5} Ci/L to 1 Ci/L), or high-level (>1 Ci/L). Solid radioactive wastes (SRWs) include metals, concrete, wood, organic films, working clothes, etc. Gaseous wastes may be provisionally subdivided into two groups: gases containing induced activity and fission product gases evolved as a result of

[1]Much of this material is taken from Egorov (1998), Bradley (1997), and Cochran *et al*. (1995). Site environmental conditions are primarily from Velichkin *et al*. (1996); data on waste management are primarily drawn from Egorov (1998).

irradiated uranium reprocessing and of further chemical and metallurgical treatment of radioactive materials (RMs). Presently, high-, intermediate-, and low-level wastes are managed at all of these nuclear enterprises.

Construction of the MCC plutonium production facility, located near the city of Zheleznogorsk, was authorized in 1950. The site is located on the Yenisei River, one of the great Siberian rivers, approximately 60 km northeast of the city of Krasnoyarsk.

A1.1 Environmental Setting

A1.1.1 Geology

The MCC occupies 15 km along the right bank of the Yenisei River. It covers a total area of about 360 km^2. The region is characterized by complex relief and is divided into mountainous and plains regions. The MCC and its associated disposal areas lie partially in a mountain area belonging to the joint zone of the West-Siberian platform and Sayan-Altay-Yenisei folded area.

The West-Siberian platform, or artesian basin, corresponds in geomorphology to the West-Siberian plain, which is one of the largest plains on earth. In the north, it opens to the Arctic Ocean; in the northeast, its boundary is the Yenisei River; and, in the south-east, it borders upon the Kustanay bank. The plain has a gradual inclination to the north only along the Ob River and the Yenisei River valleys; other parts are characterized by complex relief with a combination of low plains and heights. Consequently, the Ob and the Yenisei Rivers can be considered as the main pathways for possible migration of radionuclides from the combines (IA Mayak, SCC, and MCC) into the Arctic Ocean.

The West-Siberian artesian basin is one of the largest groundwater reservoirs on earth. In terms of tectonics, it is a two-staged structural depression. The lower stage represents a folded rock basement composed of dislocated Paleozoic metamorphic, sedimentary, and igneous rock. The upper tectonic stage is a gently sloping Mesozoic-Cenozoic sedimentary formation. The depression has an asymmetric morphology with gentle western and steeper eastern slopes. The surface of the Paleozoic basement dips in the central and northern parts of the depression to a depth of 5–6 km. The artesian basin is generally open toward the Arctic Ocean, but the surface of its Paleozoic basement is not a plain; rather, there are sequences of basins and heights that create the complicated forms of the present relief. Its relative elevation is about 300 m (the minimum true elevation is 20 m in the area of the junction of the Irtysh and Ob Rivers). Taking into account these structures, a number of researchers have identified artesian basins of the second order on the territory of the West-Siberian artesian basin. However, the regular distribution of heads in the water-bearing horizons, which are correlated to areas of groundwater recharge and flow, characterize the West-Siberian artesian basin as a unified watershed.

The Sayan-Altay-Yenisei hydrogeologic folded area is characterized by a combination of mountains, plateaus, folded zones, and intermountain depressions formed as a result of Baikalian, Caledonian, and Hercynian orogeny. The middle- and high-mountain systems are located in the southern part of the area. General lowering of ridges on the order of 500–1,000 m is noted to the west, northwest, and north. The southern part of the Yenisei Ridge, where the MCC is located, is representative of typical lowlands, with heights reaching 600–710 m above sea level and the river valley cutting 300–350 m deep.

Neotectonic movements have been the main factor in the formation of the present relief. In accordance with different ages of folded formations, one can note three complex hydrogeologic regions of the first order consisting of artesian and subartesian basins and basins of crevice waters. These are Yeniseisky (the oldest), Sayano-Altaysky (old, mainly Caledonian, the most widespread in the folded area), and Zharmino-Rudno-Altaysky (the youngest, Hercynian) hydrogeologic regions. The Yeniseisky hydrogeologic region is located at the Yenisei Ridge and is drained by the Yenisei River.

The Yenisei Ridge and northeastern slope of the Baikal Sayan surround the MCC and are related to Baikal folded formations. The Yenisei Ridge is a complex meganticlinorium built with highly metamorphosed and dislocated crystal shales and Archean gneisses. Metamorphosed terrigenous and carbonate rocks are also found. Archean and late Proterozoic rocks are broken by granitoids. The direct prolongation of the Yenisei meganticlinorium is the northeastern slope of Eastern Sayan, the so-called “chief anticlinorium” of Eastern Sayan or Protero-Sayan. It has dislocated Archean and Proterozoic gneisses, crystal shales, phyllites, migmatites, amphibolites, quartzites, marbles, and dolomites. Small intermountain depressions occur on the Baikal basement.

Deep faults with lengths of more than 500–1,000 km and large amplitude occurred during formation of structures of the Sayan-Altay-Yenisei folded area. Shear zones with widths up to 15–125 km have connections with deep faults. Most faults have a northwest orientation. The meridional zone of faults is a border between the West-Siberian artesian basin and the Yenisei Ridge and coincides with the bed of the Yenisei. Most of the deep faults are old and stable. Displacements occurred during the whole Paleozoic and Cenozoic Eras. The natural seismicity of the region is less than 6 on the 12-point MSK-1964 scale.

Plains with heights of 124–185 m are located on the right bank of the Yenisei, and are occupied by forest, meadows, ploughed fields, swamps, and a shelving slope from the south-southeast. The absolute height of this slope is 185–225 m.

The mountain part forms the base banks of the Yenisei. The Atamanovsky Ridge is one of the distant spurs of the Yenisei Ridge. The ridge represents a plateau

Table A1.1. Average and extreme monthly temperatures, °C.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
Average	–18.3	–15.9	–7.9	1.7	9.1	16.4	19.4	16.2	9.6	1.6	–9.1	–16.6	0.5
Average minimum	–38	–34	–28	–13	–6	3	7	3	–4	–14	–28	–37	–42
Average maximum	–2	2	9	18	28	32	32	31	23	18	6	1	34
Absolute minimum	–55	–44	–39	–24	–17	–3	0.3	–2	–12	–33	–47	–48	–55
Absolute maximum	6	10	17	32	35	38	40	36	33	25	14	10	40

Table A1.2. Average monthly precipitation (mm).

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
Precipitation	15	12	15	27	43	57	84	76	51	41	34	24	479

extending southeast with an absolute height of 370–420 m. The ridge is deeply cut with ravines and stream valleys. On the left bank of the Yenisei, the Atamanovsky Ridge becomes narrow and low, and gradually merges with the plain.

A1.1.2 Meteorology

The climate is strongly continental with a long, cold winter, a short, dry summer, a late spring, and a rainy autumn. The average air temperature of the coldest month (January) is –18.3°C, while the warmest one (July) is 19.4°C. The daily amplitude of air temperature ranges from 12–14°C. The average annual air temperature is slightly above zero, approximately 0.5–0.6°C. The highest temperature was measured in July (40°C), and the lowest in January (–55°C). The average monthly and extreme temperatures, in °C, are shown in *Table A1.1*.

The average air humidity of the coldest month is 83%, and that of the warmest month is 76%. Average precipitation is 479 mm/yr, with the majority (379 mm or 86%) falling between April and October. Monthly precipitation distribution is given in *Table A1.2*.

The daily maximum precipitation (67 mm) was observed on 10 July 1912, corresponding with 1% of the annual precipitation. On average, precipitation intensity equaling 2.1 mm/min occurs once every 5 years, 3.2 mm/min occurs once every 10 years, and 4.15 mm/min occurs once every 20 years.

Snow cover typically first appears in Krasnoyarsk in the middle of October, with the earliest recorded snowfall on 4 September and the latest on 9 November. The formation of a stable snow cover occurs mainly in the first 10 days of November. The maximum height of snow cover occurs in first 20 days of March, and

Table A1.3. Maximum height of snow cover (cm) with probability (from snow surveys).

Probability (%)	95	90	75	50	25	10	5	Average
Open Area	10	12	15	19	24	28	32	21
Protected Area	22	25	31	40	49	60	67	48

begins to decrease starting from the last 10 days of March. The data on snow cover height for different probabilities are given in *Table A1.3*.

Stable snow cover reduction occurs in the middle of the first 10 days of April. The end of snow cover typically occurs at the end of April. Snow density ranges from 0.15 g/cm^3 in the beginning of winter to 0.24 g/cm^3 in the first 10 days of February.

Storms are mainly observed during the warm period of the year, accompanied by cumulus, nimbus, squalls, strong showers, and hail. Winter storms are very infrequent. On average, there are 21 days with storms in Krasnoyarsk. The highest probability of storms occurs in July (37%), when storms occur on average every fourth day. Hail is observed mainly during the warm period of the year. On average, hail occurs on one or two days during the summer in the town and in years with higher storm activity, up to 5 days with hail are registered. The maximum amount of hail was registered on 19 July 1966 (20–40 mm). Snowstorms are normally observed from September to May. On average, up to 29 snowstorms occur during the year, but in the winter of 1959–1960, 50 snowstorms occurred in the town. Snowstorms occur most frequently in November and December. In 80% of the cases, snowstorms are accompanied by wind speeds of 6–13 m/sec, predominantly from the SW (72%).

Prevailing winds (occurring 55% of the time) are most often from the southwest and west. Southeasterly and northerly winds (2–4%) are the least frequent. Wind speed is minimal in July-August (2.5–2.7 m/sec). In these months, winds with speeds of 0–1 m/sec are the most frequent (10–11%). Data on wind speed are given in *Table A1.4*.

In Krasnoyarsk, winds with a speed exceeding 15 m/sec can be observed throughout the year. On average, such winds occur 33 days/yr. Most often they occur in the winter and in transitional periods between seasons, and rarely in July and August. The average number of days with strong winds is given in the *Table A1.5*.

Together with strong winds, the most danger is presented by squalls (unexpected short increases in wind speeds exceeding 15 m/sec). Squalls are accompanied by storm clouds, storms, and sometimes hail. The probability of maximum wind velocities is given in *Table A1.6*.

Wind velocities during gusts may significantly exceed the average wind velocity. For example, with prevailing low wind speeds, there is the possibility of

Table A1.4. Wind speed (m/sec) and direction.

Wind	Winter				Spring				Summer				Autumn				Year			
direction	V_A	P	V_M	P	V_A	P	V_M	P	V_A	P	V_M	P	V_A	P	V_M	P	V_A	P	V_M	P
N	2	3	9	6	3	4	12	9	3	5	10	9	2	3	9	7	2	4	12	7
NW	3	7	12	8	3	6	12	9	3	11	12	10	2	6	10	8	3	8	12	7
W	3	5	15	9	4	6	12	9	3	12	10	9	3	8	10	8	3	7	15	9
SW	3	1	17	11	3	2	10	7	3	3	9	8	3	2	12	10	3	2	17	10
S	6	4	24	15	5	6	17	12	3	5	16	13	4	6	18	15	5	5	24	15
SE	7	37	34	21	6	31	22	16	4	22	20	17	5	34	24	20	6	32	34	20
E	5	35	28	18	6	35	28	20	4	30	24	20	5	33	21	18	5	33	28	17
NE	3	8	20	12	5	10	24	18	3	12	17	14	4	8	17	14	4	9	24	15
Windless	–	28	–	–	–	13	–	–	–	22	–	–	–	21	–	–	–	23	–	–
Average period without wind per season																				
Hours		56				10				18				14				98		
%		57				10				19				14				100		

V_A = average wind speed.
V_M = maximum wind speed.
P = probability.

Table A1.5. Days with winds exceeding 15 m/sec.

Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
3.8	1.9	3.5	3.1	5.0	2.3	0.7	0.8	1.7	3.7	3.5	3.1	33

Table A1.6. Probability of maximum wind speeds.

Return period (yr)	1	5	10	15	20
Wind speed (m/sec)	25	31	33	34	35

short-term gusts of up to 36 m/sec. Maximum wind speeds are the highest for southwesterly and westerly winds and the lowest for northerly and northeasterly winds.

The probability of surface inversions and above-surface inversions (with the lower border in the layer 0.01–0.5 km) with wind speeds of 0–1 m/sec near the earth surface is given in *Table A1.7*.

Fogs in Krasnoyarsk are observed mainly during cold periods. Depending on the weather conditions, fogs in the town can be of the irradiation (with strong frost), advective, or advective-irradiation type. Ice fogs develop with low temperatures and high humidity. The maximum number of fogs occur in winter and at the end of the summer. The average number of days per year with fog is 32, of which 21 occur between October and March and 11 occur between April and September. The minimum number of days with fog (1–2 days) occurs in April and May, while the maximum number (up to 18 days per month) occurs from December to February. The average total duration of fogs during the year is 114 hours. The maximum total duration of fogs, 781 hours, was registered in 1970, and the minimum (32 hours) in 1958. The duration of fogs during cold periods is two or three times longer than during warm periods. The majority of the fogs do not exceed 3 hours.

The average annual temperature of soil at the surface in the region is 2 °C. The absolute maximum of soil surface temperature is 61°C, and the absolute minimum is –55°C. The annual distribution for soil temperatures is similar to the annual distribution of air temperature. The soil surface is usually frozen from November to March, and above zero from April to October. Average temperatures of soil surface are given in *Table A1.8*.

The average annual soil temperature deeper than 20 cm is almost constant at about 3°C, with temperature increasing with depth. Stable freezing of soil occurs in the end of October, and the maximum depth of soil freezing can exceed 175 cm. In winters with low snow cover, the depth of freezing is up to 253 cm. The minimum freezing depth is 126 cm.

Table A1.7. The probability of (a) surface inversions and (b) above-surface inversions.

	Probability of surface inversions (%)				
Month	0300	0900	1500	2100	day
(a) Surface inversions					
January	55	49	60	62	57
February	68	48	55	71	60
March	68	23	32	68	48
April	56	6	6	43	28
May	56	2	2	69	32
June	59	3	3	75	35
July	77	1	6	80	41
August	75	2	5	78	40
September	66	2	16	71	39
October	50	8	37	52	37
November	45	23	47	39	38
December	54	49	55	57	54
(b) Above-surface inversions					
January	8	10	7	7	6
February	4	10	4	5	4
March	4	9	4	5	4
April	2	3	2	2	2
May	4	2	2	2	2
June	6	2	3	2	2
July	4	3	2	2	2
August	2	3	2	3	1
September	3	7	2	2	2
October	4	7	2	3	2
November	5	9	5	7	5
December	8	14	10	7	6

Table A1.8. Average temperature of soils at the surface, °C.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
Average	–18	–16	–9	2	12	21	24	19	10	0	–10	–17	2
Average minimum	–24	–22	–17	–6	1	9	12	10	3	–4	–16	–23	–6
Average maximum	–14	–10	0	13	27	38	41	34	22	8	–6	–13	12
Absolute minimum	–55	–48	–42	–31	–19	–4	1	–2	–13	–36	–47	–52	–55
Absolute maximum	4	9	22	44	52	59	61	54	44	30	11	7	61

Table A1.9. Average discharge in Yenisei River near Bazaicha, 7 km upstream from Krasnoyarsk (Kosmakov, 1996).

	Water Discharge (m^3/sec)					
	1902–1966			1967–1986		
Month	Mean	Maximum	Minimum	Mean	Maximum	Minimum
January	597	852	382	2,356	2,950	1,140
February	523	713	355	2,557	3,550	1,140
March	491	635	322	2,486	4,200	1,210
April	1,580	3,540	597	2,606	4,350	1,430
May	6,300	10,000	2,690	3,228	5,240	2,510
June	8,930	17,300	3,730	3,239	5,460	2,640
July	5,270	9,400	2,510	3,285	5,480	2,630
August	4,060	6,290	1,850	3,442	5,400	2,560
September	3,460	5,430	1,500	3,004	4,930	2,470
October	2,290	4,450	1,060	2,454	3,290	1,910
November	967	1,740	492	2,057	2,810	1,340
December	646	990	429	2,331	3,090	1,140
Annual	2,920	3,980	1,980	2,754	4,229	1,843

A1.1.3 Hydrology

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 60 km upstream from the MCC, the river is open, not frozen, throughout the year. The average water temperature is 7°C, current speed is 1.7 m/sec, average depth is 2 m, average width is 1,000 m, and average annual discharge is 2,760 m^3/sec (Kosmakov, 1996).

The average water discharges before and after the regulation of the river are shown in *Table A1.9*. Typical variations in discharge before and after the dam (*Figure A1.1*) indicate the dampening of fluctuations in discharge provided by the dam.

The Yenisei and its 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.

A1.2 Operations at the Mining and Chemical Combine

The MCC is unique in that the major part of the facility is located underground, with the reactors and reprocessing plant in tunnels about 250–300 m underground. The

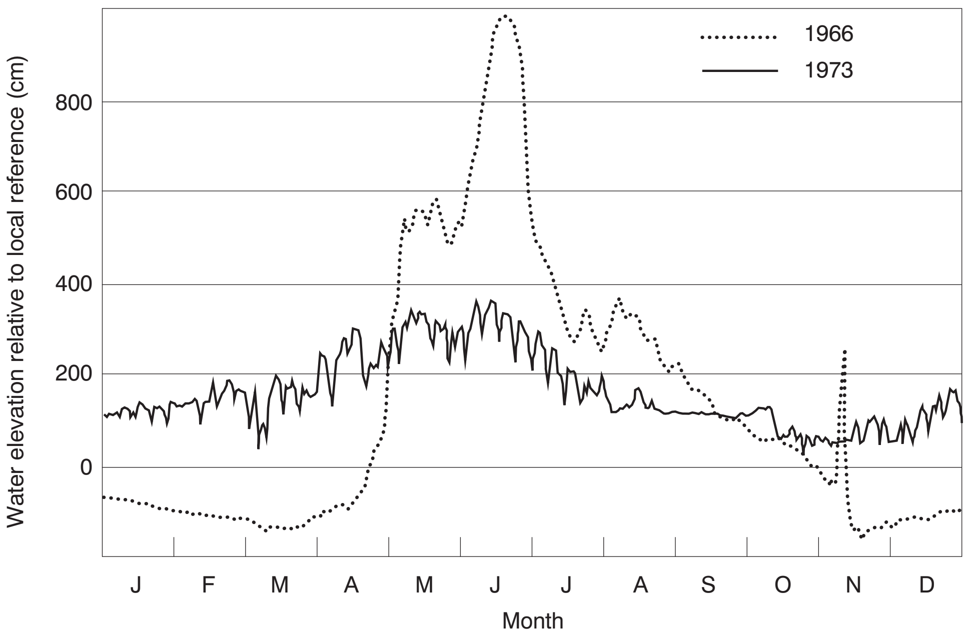

Figure A1.1. Daily variation of water level of the Yenisei River near Atamanovo, 84 km downstream from Krasnoyarsk (Kosmakov 1996).

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, and have, in contrast to the SCC and IA Mayak, a reliable isolation from the biosphere. The MCC is equipped with a ventilation system with filters that serve to reduce the emission of RMs to the atmosphere.

The first reactor (AD) was activated in 1959, the second (ADE-1) in 1961, and the third (ADE-2) in 1964. All of them are uranium-graphite and similar to civilian RBMK-type reactors. The first two reactors are likely identical to reactors for plutonium production at IA Mayak (AV-1, AV-2, and AV-3).

The first reactor (AD) was decommissioned on 30 June 1992, and the second (ADE-1) on 29 September 1992. The third reactor (ADE-2) is still operating and supplies the MCC and Zheleznogorsk with electric power and heat, although, since 1990, the output 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. Cooling water was drawn from the Yenisei River and was discharged back into the river. Therefore, RMs entered the river with the discharged cooling water. These materials were primarily from four sources: activation products due to irradiation of substances in the river water, corrosion products of the fuel cladding and structural members of the reactor, fission products from "tramp" uranium, and leakage of fission products from failed fuel elements. These past releases have resulted in radioactive contamination of river water and sediments north of the complex. The third reactor, which is still used, has a closed primary cooling cycle, which limits the amount of RM being discharged from the reactors into the river. 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.

In 1976, a decision was made to construct a new reprocessing complex (RT-2) in Zheleznogorsk for spent nuclear fuel (SNF) from nuclear power plants. Construction began in 1984. RT-2 was designed for reprocessing of SNF from VVER-1000 type reactors. The first phase of the complex, a facility for wet storage of SNF, was put into operation in 1985, and is now 30% full (the design capacity is 6,000 tons). The complex as a whole is 30–40% complete. Although the facility was scheduled to be completed by 1998, construction was halted in 1991 due to both financial problems and strong local opposition. In 1995, Russian President Boris Yeltsin approved completion of RT-2, and Minatom is currently seeking financial assistance to complete the construction. Plans are being made to set up an international company to provide funding to complete construction of RT-2. Additionally, the administration of the MCC is conducting talks with atomic industry representatives from South Korea, China, Japan, Taiwan, and some European companies to allow processing of SNF from these countries.

A1.2.1 Discharges to surface waters

Operation of the three reactors and radiochemical plant resulted in large amounts of RW. The SRWs are stored on the MCC territory. The LRW generated as a result of operations have been collected in reservoirs, partly treated, and discharged into the river or pumped into the deep wells.

Waste releases are now treated so that fixed norms are not exceeded. Releases of all radionuclides now varies from 4% to 98% of the maximum tolerated releases (MTR). The releases for two recent years are shown in *Table A1.10*.

These releases resulted in radionuclide concentrations in river water as shown in *Table A1.11*.

Table A1.10. Total amount of radionuclides in waters discharged into the Yenisei in 1993–1994, GBq/yr.

Radionuclide	Actual discharge 1993	Actual discharge 1994	Permissible discharge (PD)	Ratio 1994/1993 (%)	Ratio 1994/PD (%)
^{56}Mn	90,095	<865.8	7,400	<1	<12
^{24}Na	465,645	68,894	185,000	15	37
^{239}Np	6,364	4,366	7,400	69	59
^{76}As	3,034	1,110	5,550	37	20
^{32}P	14,800	18,093	18,500	122	98
^{64}Cu	10,915	1,036	5,550	9	19
^{51}Cr	7,104	4,181	14,800	59	28
^{59}Fe	51.8	29.6	185	57	16
^{54}Mn	16.28	11.1	148	68	8
^{58}Co	78.81	74	370	94	20
^{60}Co	103.6	77.7	370	75	21
^{46}Sc	59.2	29.6	370	50	8
^{65}Zn	70.3	48.1	370	68	13
^{140}Ba	51.8	44.4	370	86	12
^{131}I	61.05	51.8	555	85	9
^{144}Ce	111	25.9	370	23	7
^{141}Ce	15.91	5.18	185	33	3
^{103}Ru	10.36	8.88	185	86	5
^{106}Ru	40.7	13.69	370	34	4
^{137}Cs	54.39	44.4	111	82	40
^{134}Cs	2.59	2.59	29.6	100	9
^{95}Zr	54.76	25.9	370	47	7
^{95}Nb	57.35	22.2	370	39	6
^{90}Sr	51.8	22.2	74	43	30
^{152}Eu	18.5	5.92	185	32	3
^{154}Eu	8.88	2.96	37	33	8
^{124}Sb	136.9	55.5	370	41	15
Total $\beta - \gamma$ activity	62,160	99,160	251,600	160	39

Data further downstream was collected during a September 1994 expedition of the Krasnoyarsk Gidromet (hydrometeorological service). The concentration of ^{90}Sr and ^{137}Cs in the river water are given below in *Table A1.12*.

Data on activity releases prior to the shutdown of the single-pass reactors was unavailable. Since the AD and ADE-1 single pass reactors were shutdown in 1992, 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

Table A1.11. Annual concentrations of radionuclides in surface waters of the Yenisei in 1994 in zone of impact of the MCC, Bq/L.[a]

Radio-nuclides	V. Dodonovo (17 km upstream of discharge 2a)		250 m downstream of discharge 2a[b]		1 km upstream of V. Bolshoi Balchug (~10 km downstream of discharge 2a)	
	Average	Maximum	Average	Maximum	Average	Maximum
^{56}Mn			<3.0	<3.0	<1.9	<1.9
^{24}Na			19	33	2.3	3.7
^{32}P			1.9	4.6	0.44	2.5
^{51}Cr			0.52	0.96	0.10	0.20
^{54}Mn			<0.0020	0.0041	<0.00074	<0.00074
^{58}Co			<0.0044	0.012	<0.0015	<0.0015
^{60}Co			0.011	0.017	0.0030	0.0074
^{46}Sc			0.0052	0.0074	<0.0019	<0.0019
^{65}Zn			0.0078	0.016	<0.0037	<0.0037
^{137}Cs	0.0015	0.0037	0.014	0.018	0.0048	0.0081
^{95}Zr			<0.0037	0.0081	<0.0037	<0.0037
^{95}Nb			<0.0037	0.0037	<0.0074	<0.0074
^{90}Sr	0.0044	0.0052	0.0078	0.0085	0.0044	0.0056
MED from water surface (uR/hr)[c]	0.9		15		10	

[a]Differences in detection limits may be due to a variety of causes including different laboratories, different instruments, different days, and different levels of contamination.
[b]The main discharge point, 2a, is located 85 km below the dam.
[c]MED = mean exposure dose.

Table A1.12. Radionuclide concentration in Yenisei River water in 1994 (Bq/L).

Distance downstream from discharge 2a (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

system of the dual-purpose ADE-2 reactor. Velichkin *et al*. (1996) have reported data on effluent activities from the MCC in the period following shutdown of the single-pass reactors. The activity of the water discharged into the Yenisei River is in the range of 1.2–7.0 times DC_B (the allowable dose concentration for the general population outside the site) 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 at 500 m from the discharge location downstream, and 0.015 DC_B at 15 km downstream from the discharge location (1 km upstream of Bolshoi 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 Sv per year (0.5 millirem per year) at Bolshoi Balchug. After decommissioning of the single-pass reactors, the water surface exposure rate and summed activity of all radionuclides 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 for 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 downstream of the MCC discharge location, there are limited areas with exposure rates of 30–200 μR/h (Khizhnyak, 1995), with the highest values located within 15 km of the discharge area. 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 as high as 21,000 m^3/sec, and have led to deposition of suspended bottom sediments containing radionuclides on islands and floodplains (Kosmakov, 1996).

As of 1 January 1996, the area of contaminated lands was 779 ha. The lands are contaminated primarily with ^{137}Cs and ^{90}Sr radionuclides. The data on the contaminated lands are presented in *Table A1.13*. More than 5.7 km^2 of the total contaminated land area are at the underground LRW disposal site territory and at basins 354, 354a, 365, 366.

The bottom deposits of the Yenisei downstream of the discharge sites are contaminated mainly with long-lived radionuclides such as ^{60}Co (T_h=5.3 year), ^{137}Cs (T_h=30 years), and ^{152}Eu (T_h=13.3 year), due to the discharges of previous years.

A1.2.2 Atmospheric releases

The releases to the atmosphere from the MCC for 1994 are given in *Table A1.14*.

Table A1.13. Contaminated lands at the MCC (dose rates as measured in the field).

Distribution of the contaminated lands area by the exposure rate level, μR/h	Contaminated lands area, (ha)			
		Including the territories of		
	Total	production zone	sanitary and 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
240–1,000	5		5	
More than 1,000	6.2		6.2	

Source: Egorov, 1998.

Table A1.14. Radionuclide releases into atmosphere from the MCC in 1994, GBq/yr,

Radionuclides	Actual releases		Norms	
	Total	Without clean up	Maximum tolerated release (MTR)	Permissible releases
^{41}Ar	261,220	183,520	4.6×10^8	1.5×10^6
Other inactive gases	55,130	–	2.5×10^8	5.9×10^5
$\sum\alpha$	0.06	0.04	2.0×10^3	7.4
^{131}I	4.97	–	1.2×10^3	190
^{90}Sr	0.72	0.56	2.3×10^3	15
^{137}Cs	1.71	1.52	2.2×10^3	19
^{95}Zr	5.88	5.37	1.6×10^3	74
^{95}Nb	9.51	8.44	2.1×10^5	150
^{103}Ru	5.49	5.22	1.9×10^5	48
^{106}Ru	12.0	11.1	4.0×10^5	81
^{141}Ce	0.37	0.30	2.7×10^4	3.7
^{144}Ce	8.07	6.92	3.3×10^5	110
^{51}Cr	5.55	5.55	8.9×10^5	140
^{59}Fe	0.37	0.33	5.0×10^3	3.7
^{58}Co	0.37	0.11	7.1×10^3	3.7
^{60}Co	0.37	0.19	94	3.7
^{140}Ba	0.37	0.33	1.7×10^4	3.7
^{134}Cs	0.01	–	1.1×10^4	1.9
^{65}Zn	0.85	0.81	6.0×10^4	7.4
^{46}Sc	0.17	0.15	5.0×10^3	3.7
^{54}Mn	0.18	0.15	6.0×10^3	3.7
^{32}P	65.19	39.15	9.0×10^4	560

Source: Velichkin *et al.*, 1996.

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

- At the industrial site – 4.8 and 8.1 (Bq/m^2)/yr (1 km north of source of release).
- In the sanitary-protective zone – 6.9 and 3.9 (Bq/m^2)/yr.
- In the zone of observation – 4.2 and 5.0 (Bq/m^2)/yr (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 eightfold. In the nearest settlements (the Bolshoi 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 and protective zone and of the observation zone is practically indistinguishable from global background levels.

A1.2.3 SRW disposal

As a result of the MCC operation, large amounts of liquid and solid high-, intermediate-, and low-level RWs have been generated. The solid wastes are divided into three groups defined by gamma-exposure rate measurements made at the surface of the waste solids. Group I wastes are those with a gamma EDR of 0.015–5.5 μR/sec; Group II, 5.5–250 μR/sec; and Group III, > 250 μR/sec. Typically, Group I wastes comprise household rubbish, deteriorated work clothes and footwear, breathing apparatuses, packaging materials, cleaning cloth, wooden containers, wastes of repair shops, dismantled washed-out equipment, tubing scrap, building refuse, etc. Group II wastes comprise graphite bushing, fuel channel briquettes, deteriorated metallic components, radiochemical laboratory glassware, building refuse, filters, etc. Finally, Group III wastes comprise instrument sensors, wastes from repair and construction work at radioactively contaminated sites, RM spreads and spills, radiochemical production works' SRW that contain alpha-emitting nuclides, etc.

The SRWs and LRWs are kept in storage facilities on the MCC territory. These facilities consist of a variety of earthen trenches, reinforced concrete reservoirs, and underground shafts in the complex. Group I wastes are stored in seven filled earthen trenches in compacted loam. As soon as the trenches are filled, they are covered by a 1-m-thick soil layer. Group II and III wastes are located in reinforced concrete facilities. There are four reinforced concrete reservoirs, deepened into the ground. Their bottom is made of a layer of compacted crushed rock 70-mm thick that is impregnated with bitumen and covered by an asphalt layer 35-mm thick. These facilities contain fine granular SRW of Groups II and III in shielded containers, as well as large-sized SRW of Groups II and III. Within the underground complex, four reinforced concrete shafts lined with stainless steel contain Groups II and III reactor SRW. The solid waste storage facilities are summarized in *Table A1.15*.

A1.2.4 LRW disposal

Depending on their activity level, LRWs resulting from production operations are either sent to cleaning facilities or collected in special tanks or in open storage reservoirs. After treatment and cleaning, liquid wastes are sent to underground disposal at the Severny site and decontaminated waters are discharged into the Yenisei River. The facilities for handling LRW at the MCC comprise a variety of tanks, basins, sludge storage facilities, and the deep well injection facility at the Severny site.

The high-level LRW storehouse, located within the underground complex, is a facility comprised of 24 stainless steel, 300-m^3 tanks placed in canyons. The walls of the canyons are lined with stainless steel. Each canyon is covered by a concrete plate 1 m thick, and the tanks are provided with coil coolers. The high-level solutions from the radiochemical plant are received for storage and processing.

The medium-level LRW storehouse is an underground facility comprised of 17 reinforced concrete tanks. Nine of the tanks have a storage capacity of 3,000 m^3; the remaining eight are 8,500-m^3 tanks. The tanks are lined with stainless steel or with carbon steel with epoxy coating. The tanks are equipped with systems for circulating air to prevent gas buildup and for cooling of the solutions. The liquid medium-level wastes are received from the radiochemical plant.

There is also a medium-level pearlite sludge storage facility, comprised of a stainless steel tank placed in a compartment with concrete walls reinforced with stainless steel. The sludge contains 50 m^3 of solids, and radionuclides from process solutions.

Aboveground basins are also used for liquid management. Basin 365 is an open water reservoir located on the first super floodplain terrace of the Yenisei River, approximately 100 m from the river and 50 m above the level of the river. It is designated for receiving and storing reactor emergency waters and off-grade nonprocess wastewaters of the radiochemical plant before they are sent to cleaning facilities. Protection of the underlying groundwater is provided by a clay layer, two asphalt layers on the bottom and slopes, as well as by bottom and bank drainage systems for interception and leak detection in case of damage to the liners. Basin 366 is an open water reservoir, located on the first super floodplain terrace of the Yenisei River, approximately 100 m from the river and 50 m above the level of the river, near basin 365. It has been built by hydraulic deposition of soil and is

Table A1.15. SRWs at the MCC (as of 1995).

Characterization of storage site		Time period of operation		Filling volume, thousand m^3		Area	RW amount
		Start	End	Design	Actual	($10^3 m^2$)	(tons)
Group I	Seven earthen trenches in compacted loam	1963–83		111.6	109.6	38.3	52,170
Groups II and III	Four reinforced concrete reservoirs Four reinforced concrete shafts	1963		27.4	24.2	5.0	53,000
						Total	105,170

Table A1.16. LRWs at the MCC (as of 1995).

Storage site and characterization	Start of operations	Volume (1,000m^3) Design	Volume (1,000m^3) Actual	Area (1,000 m^2)	Amount of RW (tons)	Activity Specific (Ci/L)	Activity Total (Bq)
High-level LRW storehouse	1963–73	6.84	2.02	4.4	2,020	up to 1.9×10^{13}	3.1×10^{18}
Intermediate-level LRW storehouse	1964–65	94.55	53.1	4.0	53,000		8.1×10^{17}
Medium-level pearlite sludge storage facility	1986	0.5	0.17	0.078	170		
Storage basins	1958–66	794	520	130	566,800		1.4×10^{15}
Severny underground LRW disposal site	1967	11,000	5,000	6,300	5×10^{6}	1.8×10^{5} to 1.5×10^{11}	1.1×10^{19}
Total		11,896	5,575	6,439	5,622,000		1.5×10^{19}

designated for reception of decontaminated (in accordance with the set standards) waters from the Combine's cleaning facilities. The basin provides for holding, settling, and filtration of wastewater before their discharge into a stream that drains into the Yenisei River. The water filters through the bottom and the dam body. In the event of excessive filling, the water can be discharged over a spillway into the Yenisei River

Basin 354a is an open pit water reservoir, built in essentially impermeable rocks. It is designated for reception, composition balancing, and interim storage of regeneration solutions and sludges from cleaning facilities, as well as of low-level wastes and condensate after evaporation of the radiochemical plant process wastes before sending them to underground disposal. Groundwater protection is provided by a two-layer liner on the bottom and slopes, which is equipped with a drainage system between the liner layers. In addition to the engineered geological and hydrogeological structure of the area, the presence of a thick covering of uniform and essentially impermeable clays provides protection. Basin 354 is situated 100 m from basin 354a on a site with similar engineered geological and hydrogeological conditions. Its design is similar to those of the basin 354a. At present, the basin is completely emptied and is being eliminated.

The LRW storage facilities are summarized in *Table A1.16*. The majority of the wastes are injected underground. The specific details of the Severny injection site are given in Chapter 2 of the main report.

Appendix 2

Excerpt from United States Regulations on Injection of Wastes

40 CFR148.20(a)[1]: Sec. 148.20:[1]
Petitions to allow injection of a waste prohibited under subpart B.

(a) Any person seeking an exemption from a prohibition under subpart B of this part for the injection of a restricted hazardous waste into an injection well or wells shall submit a petition to the Director demonstrating that, to a reasonable degree of certainty, there will be no migration of hazardous constituents from the injection zone for as long as the waste remains hazardous. This demonstration requires a showing that:

(1) The hydrogeological and geochemical conditions at the sites and the physiochemical nature of the waste stream(s) are such that reliable predictions can be made that:

(i) Fluid movement conditions are such that the injected fluids will not migrate within 10,000 years:

(A) Vertically upward out of the injection zone; or

(B) Laterally within the injection zone to a point of discharge or interface with an Underground Source of Drinking Water (USDW) as defined in 40 CFR part 146; or

(ii) Before the injected fluids migrate out of the injection zone or to a point of discharge or interface with USDW, the fluid will no longer be hazardous because of attenuation, transformation, or immobilization of hazardous constituents within the injection zone by hydrolysis, chemical interactions, or other means.

[1]CFR = Code of Federal Regulations.

Appendix 3

Green Cross Summary of the Conclusions of the Expert Commission of the Regional Center for Radioecological Investigations and the Response of VNIPIPT and MCC

Summary of the Conclusions of the Expert Commission

Based on the facts stated above, the commission conducting an independent ecological-technological examination of the Severny storage ground for LRW burial of the Krasnoyarsk MCC came to the following conclusions:

- The Severny storage ground is a man-made radioactive deposit presenting high potential ecological hazard.
- The extent to which the territory of the Severny storage ground has been investigated in terms of geology, as well as detailing and interpretation quality of the materials of geological prospecting at the stages of surveying and operation do not conform to current requirements imposed on such facilities. It means that the statement made by the MCC geological department that the storage ground is securely isolated from the Yenisei riverbed and the riverbed of its tributary, the Bolshoi Tel River, by the tectonic and lithofacial screens is not convincing and in some instances it is in contradiction with the facts. This discrepancy casts doubt on the statement that the further operation of the storage ground is safe. The velocity of the filtrate flow in the northward direction to the middle reaches of the Bolshoi Tel River is 350 m/yr in the second stratum and 250 m/yr in the first. There is 2 more km to the river, the discharge area, which is comparable with the distance already covered.
- The effect of the Severny storage ground on the ecological state of the environment of the region is not understood enough to make a decision of proceeding with the construction of the RT-2 plant.
- Field explorations aimed at estimating the radiation situation in the ground allotment along the main pipeline of the Severny revealed the repeated violation of the process regulations, which resulted in local and sectional contamination of some plots.

Response of VNIPIPT and the MCC

"Short Reference on the Results of the Ecological and Technological Expertise of Radioactive Waste Disposal Site, Given in the Green Cross Report About the After-Effects of the Krasnoyarsk Mining and Chemical Combine (MCC) Activity" (see above).

The following reference presents a brief response to critical remarks prepared by ecological experts. More detailed information is presented in reports of VNIPIPT and the MCC.

1. Insufficient application of aerial geological survey methods during initial phases of prospecting work (1955–1965) was one of the drawbacks mentioned by the expertise (p.1.1). It should be pointed out that flights were forbidden as a result of the secrecy regime in the area of the MCC. This was compensated by drilling many wells and by electro- and seismo-prospecting.
2. The absence of a conditioned 1:50,000 scale geologic survey was another drawback mentioned in the expertise report. It should be pointed out that the above-mentioned survey was not carried out due to the regime of secrecy. Nonetheless, exploration of the disposal area significantly exceeds the survey requirements. In response to this remark and others analogous to it, it should be noted that the authors of the ecological-technological expertise most likely were attempting to justify funding for new work that would be performed by geological and research organizations of Krasnoyarsk Krai.
3. The expertise states that geomorphological, hydrogeological, and other studies were not carried out in the above-mentioned area during last 30 years. It should be noted that in reality, waste disposal was accompanied by regular hydrodynamic monitoring, geophysical measurements, and sampling of ground water. In 1988–1991, geomorphological studies to detect effects of neotectonic and current geologic processes were carried out (MGRI, N.V. Lukina), permanent seismic observations were organized, and high-precision geodetic surveillance was conducted (OKB IFZ). Electrometric studies by means of the AMTZ-method have been performed since 1996 (St. Petersburg State University).
4. The main tectonic structures were detected during surveys and prospecting work. The most important of the above-mentioned structures – the Right-bank Tectonic Disturbance – was explored by filtration tests using pairs of wells located on both sides of the disturbance plane. Therefore, the assertion of the expertise authors that "disjunctive tectonics has not been practically studied" is not correct (p.1.3). Well drilling through the tectonic zone was not carried out, in order to avoid loosening of the clay layer sealing the disturbance. The difference of water heads on both sides of the surface is 0.4 MPa. The sealing failure which could result from well drilling could make disposal impossible.

5. Test of rock specimens is not a major method of evaluation of geological cross-section characteristics for water-bearing horizons investigation, nor for water-supply and waste injection, nor for oil horizons studies. It is therefore not necessary to provide for 100% extraction of the core samples in this case. Geophysical and filtration tests are more important, and are why the expertise remarks, mentioned in p.1.5, should not be considered.
6. Trying to prove unevenness of horizons squares, the authors compare well sections located in rather different structural conditions (p.1.6). For instance, the C13 well, which is situated 7 km from the center of the site, outside the allotment area, and where some horizons might be diminished, is compared with the central wells. The P12 well is located in the downthrown block and the P8 well is located in the upthrown block, where Horizon II is absent. The direct comparison of these wells without consideration of their position is therefore not correct. This reflects the tendentiousness of the expertise authors. Well C22 is also situated where structural conditions differ from the conditions of the central part of the site.
7. According to the results of our analyses, the “A” horizon, which underlies Horizon I, is present in all wells of the central area of the site, and absent in peripheral areas of the Site, in the slopes of crystalline basement in areas inaccessible for wastes. Despite the expertise statement, the “A” horizon is identified in the P3 well, and its thickness is 13 m.
8. According data from many years of studies, increased migration of wastes in the strata of brown coal was not observed.
9. Special studies of neotectonics were carried out in 1988–1991. There are official reports of the independent institution which carried out the observations. From these reports it follows that the data on rock uplifts of up to 12.4 mm, cited in the expertise report, are not correct.
10. In the process of discussing the results of filtration tests carried out in the area of the Tectonic Disturbance, the expertise authors consider the erroneous thesis that the fractured zone is permeable and that water flows through it into a pumping zone (p.2.2). This is not correct. On the basis of the difference of water heads between the upthrown and downthrown blocks (0.4 MPa), it is possible to conclude that the fault zone is impermeable, and the water flow through it is impossible. Similar erroneous theses are used in p.2.3, where the hydrology of the Site is considered. Interconnection of I and II horizons with surface water in the valley of the Bolshoi Tel River does not necessarily indicate a hazardous situation. MCC carried out special investigations on the interconnection of the horizons in the Bolshoi Tel River valley.
11. The affirmations, that the rate of waste migration is 350 m/yr in Horizon II and is 250 m/yr in Horizon I, are not correct. The migration of waste components

was not more than 500–800 m over the last 30 years (p.2.4). (See data on waste dispersal contours).

12. The increased gamma radiation within the Disposal Site and on the delivery pipeline were detected within the sanitary-protective zone and in areas where radioactive wastes are handled, such as pumping stations, waste receivers, pipelines, sampling equipment, etc. Radioactive soil contamination was observed in areas where the pipeline was repaired and where armature leakage occurred. All contaminated places are within the sanitary-protective zone and can be remediated.

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