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# Radionuclide Contamination at Kazakhstan's Semipalatinsk Test Site: Implications on Human and Ecological Health

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## Abstract

A delegation of five scientists participated in a U.S. National Research Council program to review the status of research on the health and environmental impacts of nuclear testing at the Semipalatinsk Test Site (STS) in eastern region of the Republic of Kazakhstan. From 11 August through 25 August, 2000, we visited several research institutes in Kazakhstan and consulted with numerous Kazakh researchers from academic disciplines ranging from radioecology to public health and medicine. We focused on reviewing data on the health and environmental impacts resulting from the testing. The health effects caused by the testing at STS have received a fair amount of study, and research using modern techniques such as fluorescence *in situ* hybridization and nuclear magnetic resonance will likely increase the reliability of dose reconstruction. However, the extent to which the STS is contaminated has not been adequately characterized, and the potential exposure to nomadic peoples and ecological receptors at the uncontrolled test site is not known. Additional research in these areas, and development of administrative controls for the site, appears warranted.

**Key words**: Kazakhstan, Semipalatinsk Test Site, radionuclides, site characterization, health effects, ecological impacts

# Introduction

The Republic of Kazakhstan (Figure 1) gained its independence on 16 December 1991 with the dissolution of the Soviet Union and is now part of the Commonwealth of Independent States (CIS). During the Soviet period, the Semipalatinsk Test Site was established about 150 km west of the city of Semey (also known as Semipalatinsk), in northeastern Kazakhstan (Gusev et al. 1997). The central, and most secret, portion of the site is a 170 – 200 $km^2$ area known as the "Polygon" which was the local control center for nuclear testing (Hayes et al. 2000). The Polygon covers a portion of the northwestern part of the East Kazakhstan oblast (formerly known as the Semipalatinsk oblast), as well as parts of the Pavlodar and Karaghandy oblasts (oblasts are administrative units, similar to states in the U.S.).

A reported 498 nuclear tests were conducted by the Soviet Union at the STS during the 40-year period between 1949 and 1989 (Gusev et al. 1997). The first nuclear test conducted at STS was on 29 August 1949 and was a plutonium bomb which yielded about 22 kT of explosive power and was reported to be a copy of the U.S. "Fat Man" design (Mikhailov 1996 in Simon 2000). Between 1949 and 1962, the Soviet Union conducted 118 atmospheric nuclear and thermonuclear tests, 26 of them near the ground (Gusev et al. 1997). The approximate cumulative explosive yield of these tests, 6.4 MT, is about 6 times greater than the explosive yield of the above ground tests at the Nevada Test Site and about 6% of the yield of the tests conducted in the Marshall Islands (Simon 2000). In addition, in 1965, two additional atmospheric tests with deliberate soil excavation were conducted (Gusev et al. 1997). Although above-ground testing was terminated in 1962, vented underground detonations occurred through 1989. The last test took place on 12 February 1989 and resulted in a leakage of large amounts of the radioactive noble gases xenon and krypton (Gusev et al. 1997). The radionuclides emanating from these tests resulted in atmospheric and environmental contamination (Peterson et al. 1998). Testing at the site ceased in 1989, and in July 2000 an international team of scientists conducted a controlled detonation of 100 tons of explosives in the final remaining tunnel of the Polygon, effectively ending Kazakhstan's status as a nation capable of testing and launching nuclear weapons (Associated Press 2000).

Our delegation of five scientists was sent to Kazakhstan by the U.S. National Research Council as part of a program to review the status of research on the health and environmental impacts of nuclear testing at the STS. The program was supported by the U.S. State Department through the Research and Training Program for Eastern Europe and the Newly Independent States of the Former Soviet Union (Title VIII) program. The purpose of Title VIII is to support the development of American expertise in the former Soviet Union and Central Europe with the understanding that these experts can then share their expertise with the government. The program is administered by the National Research Council (NRC), the operating arm of the National Academy of Sciences. The National Research Council promotes international collaborations, particularly among younger specialists, as a way to increase knowledge in general.

Our team examined the health and environmental impacts of nuclear testing at the STS. In addition to direct exposure from past testing, we examined issues related to current exposure from contaminated soil and migration of radionuclides into drinking water supplies as well as other dietary and lifestyle factors which may compound the problems of radiation. Our team was composed of a genetic epidemiologist, a radiobiologist/cytogeneticist, a cultural anthropologist, a chemist/air quality specialist, and an ecologist/environmental scientist. A representative from the NRC also joined the group as the sixth member of the delegation.

We visited Kazakhstan to meet and discuss these issues with researchers investigating the health and environmental impacts resulting from this legacy of nuclear testing. We visited several institutes both in Almaty and Semipalatinsk and met with numerous researchers. Details of the institutes we visited and researchers with whom we spoke are found in Carlsen 2000 and are available upon request.

## Radiation Dose Reconstruction

Research into the health effects of nuclear testing on populations living near STS has primarily involved internal and external dose reconstruction and epidemiologic investigations on dose-response relationships. Initial research focused on dose reconstruction of four surface tests (Gusev et al. 1997, Simon 2000) and the determination and tracking of cancer rates of individuals residing near the test site at the time of the testing (Gusev et al. 1998, Peterson et al. 1998, Hayes et al. 2000). The majority of the exposure occurred in four regions (Abaysky, Zhana-Semeysky, Beskaragaysky and Abralinsky) within the Semipalatinsk oblast, with an average exposure of 2000 mSv (Gusev et al. 1997), although there is some disagreement on the actual dose received by the residents (Simon 2000). Several recent inquiries into the available information for historical dose reconstruction indicate a lack of meteorological data collected during testing.

Cytogenetic biodosimetry studies will help identify the uncertainty distribution of cumulative dose from both internal and external exposures. There have been a few cytogenetic studies completed to date on the effects of test-related radiation exposure in people living near the STS and in areas downwind from the site. The most consistent result of these studies is an observed elevation in the frequency of unstable chromosome aberrations (micronuclei) in peripheral blood lymphocytes, which may be related to proximity to the STS (Ilyinskikh et al., 1997, Tanaka et al. 2000). We met with scientists at the cytogenetic laboratory in the Institute of Radiation Ecology and Medicine in Semipalatinsk, where studies using modern biodosimetric techniques such as fluorescent *in situ* hybridization (FISH) are now underway, and should facilitate the estimation of cumulative, lifetime exposure to ionizing radiation in affected individuals. In addition, we met with researchers at the Institute of Nuclear Physics near Almaty, which has a new Laboratory of Nuclear Magnetic Resonance (equipment purchased by the Japanese government). This laboratory is being used to conduct electron spin resonance studies to provide physical dosimetry estimates from bone and soil samples to reconstruct external doses.

## Health Effects Studies

One of the first, and possibly only, etiologic epidemiologic investigations conducted to date (Abylkassimova et al., 2000) was a nested case-control study of leukemia within a cohort of 10,000 exposed subjects under continued follow-up (Gusev et al., 1998). Subjects were comprised of 22 leukemia cases (except chronic lymphocytic leukemia) and 132 age- and gender-matched controls. Results suggest nearly a two-fold risk of leukemia (OR=1.91, 95%CI 0.38-9.67) among those with doses >2 Sv compared with those having doses <0.5 Sv. The authors concluded that results could be biased by chance findings due to the low number of cases studied. A descriptive study (Zhumadilov et al, 2000) reported the frequency distribution of thyroid abnormalities among 7,271 patients (10.5% male, 89.5% female) from the Semipalatinsk (N=1,683), Ust-Kamenogorsk (N=2,032), and Pavlodar (N=1,142) regions. From 1982-96 there was an increase in Hashimoto's thyroiditis and thyroid cancer compared with before 1982 when more testing occurred. Papillary cancer (48.1%) and follicular (33.1%) predominated in the Semipalatinsk region. During 1987-96, there was an increase in the number of cases among patients less than 40 years of age, with the highest proportion below age 20 in Semipalatinsk and Ust-Kamenogorsk. A significant cancer-period interaction and increasing trend in the proportion of cancers out of the total abnormal cases was identified. The authors recommended that analytic etiologic studies of thyroid disease be conducted among populations exposed to radionuclides from the STS.

The majority of the scientists and researchers we encountered during the visit agreed that the currently observed health effects are a result of exposure during the period of testing, and not a consequence of exposure to residual radioactivity. This is not surprising, given the predominance of short-lived radionuclides in the atmospheric tests. About 64% of the dose received by the near-by populace as a result of fallout occurred during the first week, and about 85% during the first three months after the explosion (Gusev et al. 1997). The current dosimetry data reviewed above, as well as the existing residual environmental activity present in the villages (discussed below), tend to support this claim. However, some Kazakh scientists are of the opinion that residual radioactivity is not responsible for ongoing health impacts. The most notable scientist expressing this view is Prof. Saim Balmukhanov, the prominent director of the Institute of Oncology. During our meetings with Prof. Balmukhanov, he presented data collected on the populations of the villages of Sarzhal, Kainar (both exposed) and Kokpecty (an unexposed control group) through 1999 on pathologies other than cancer. Pathologies in cohorts born after the atmospheric tests appeared to be significantly higher in the villages within the fallout isolines compared to the control village. Prof. Balmukhanov made a particular case that various pathways of exposure to plutonium particles from the soil may be a causative agent in these pathologies (such as alpha particles causing skin damage, or plutonium accumulation in the bones of horses, and subsequent consumption of food dishes made from horse bones). While it was not possible to determine if standard epidemiological techniques were used in Prof. Balmukhanov's work, he raised interesting questions which may merit further examination (Balmukhanov, 1999). There is little doubt that people living in the STS region suffer from a range of adverse health effects, including high rates of infectious and noninfectious diseases, cancer, and hematological disorders. However the task of definitively relating any of these effects to nuclear weapons testing will be complicated by numerous confounding factors such as inadequate nutrition, poor water quality, and unsanitary living conditions (Logachev et al., 1998).

## Natural Resource Use By The Local Population

In order to gain a better understanding of how the local population used the natural resources in and adjacent to the STS, two days were spent visiting villages near the border of the STS. The villages visited were Sarzhal, Kanonerka, Bolshia Vladimirovka and Dolon (Figure 1). The population of these villages ranged from 800 to 4,800 people. These villages all received significant effective doses through 1960, with Dolon receiving 4470 mSv, Sarzhal receiving 2460 mSv and Kanonerka receiving 1790 mSv (Gusev et al. 1997). Agriculture and livestock production were the economic bases of all villages visited. In general, cattle were ranged on lands adjacent to the villages, but more distant ranging was occasionally conducted. Pigs were generally maintained closer to the village. Most homes had private gardens, and all villages relied on ground water as the sole source of drinking water, with any surface water present used only for livestock. Other natural resource use (such as hunting, and collecting berries and native grasses) occasionally occurred at some distance into the STS. More details on the village visits can be found in Carlsen 2000.

## Residual Environmental Contamination

The STS is located in the plains of the dry Eurasian steppe. It is comprised primarily of steppe grassland dominated by the family Poacea (primarily the genus *Stipa* ) and the genus *Artemisia* from the Asteracea family (Tarasov et al. 1997). Higher slopes have stands of monospecific forests composed of Scots Pine (*Pinus sylvestris*) (Kremenetski et al. 1997). Steppe fauna includes a number of small rodents (such as kangaroo rats and ground squirrels) and hares. Mammalian predators include the wild cat, steppe cat, steppe fox and skunk. Several ground nesting birds such as pheasants are present. Grazing ungulates include the steppe antelope, goats and the migratory saiga antelope. Raptors include the large steppe eagle (Kazakhstan State National University Natural History Museum, 2000). Two rivers occur near the borders of the STS, the Irtysh north of the site, which runs through Kurchatov, Shaghan and Semey, and the Shagan river on the eastern border of the site, running south from Shagan to Sarzhal (Figure 1).

Since testing ceased at the STS, a limited amount of work has been done to characterize the environmental contamination at the site and its surrounding environs (Tables 1 and 2). Shebell and Hutter (1998) and Dubasov (1997) describe results from an International Atomic Energy Agency sponsored expedition conducted in July 1994. Shebell and Hutter (1998) presented results from the American team from the U.S. Department of Energy, whereas Dubasov (1997) described results from the Russian team from the Khlopin Radium Institute. These papers describe results from soil samples collected near "ground zero" of the first thermonuclear explosions at STS, from a crater alternatively called "Bolapan" or "Chagan" which was formed by an underground nuclear explosion in 1965 along the Shagan River, and from several nearby villages. Hill et al. (1998) present data on existing external doses, human body burdens, and residual environmental contamination at the villages of Mostik and Maisk. This study was conducted in 1995 by an international team of Kazakh, French, Czech and German scientists at the villages of Mostik and Maisk. Mostik is located near Dolon within the trace of the first atomic bomb test. Miask is a small village near Kurchartov and was not within the bomb trace.

Residual soil activity at the STS reported by Dubasov (1997) was lower in all cases than those reported by Shebell and Hutter (1998) and Yamamoto et al. (1996) (Table 1). Samples from near ground zero and the Chagan/ Bolopan site contained elevated levels of $^{137}Cs$, $^{60}Co$, $^{152}Eu$, $^{154}Eu$, $^{239,240}Pu$ and $^{241}Am$, which resulted in a significantly elevated external dose. Weapons-grade plutonium was detected in samples collected from both sites by Yamamoto et al. (1996).

**Table 1. Summary of maximum activities in soil at the STS.**

| | **Dubasov 1997** | **Shebell & Hutter 1997** | **Yamamoto et al 1996** |
|---|---|---|---|
| **Sample type** | **Composite samples from 0-20 cm** | **Individual subsamples of 0-5, 5-10 and 10-15 cm** | **Surface samples to 5 cm** |
| **Vicinity of Ground Zero ($Bq \cdot kg^{-1}$)** | | | |
| **n** | **7** | **6** | **1** |
| **$^{137}Cs$** | **108** | **24200** | **83300** |
| **$^{60}Co$** | **<2** | **1650** | **5410** |
| **$^{152}Eu$** | **17** | **39220** | **96100** |
| **$^{154}Eu$** | **<6** | **679.3** | **2910** |
| **$^{239,240}Pu$** | **488** | **–** | **27900** |
| **$^{241}Am$** | **52** | **435.9** | **520** |
| **External Dose[a]** | **0.21 $\mu Gy \cdot hr^{-1}$** | **22.4 $\mu Gy \cdot hr^{-1}$** | **30 $\mu Sv \cdot hr^{-1}$** |
| **Chagan/Bolapan site ($Bq \cdot kg^{-1}$)** | | | |
| **n** | **1** | **1** | **2** |
| **$^{137}Cs$** | **1500** | **21550** | **22600** |
| **$^{60}Co$** | **356** | **21840** | **20500** |
| **$^{152}Eu$** | **321** | **16900** | **17200** |
| **$^{154}Eu$** | **585** | **11430** | **10400** |
| **$^{239,240}Pu$** | **192** | **–** | **8850** |
| **$^{241}Am$** | **24** | **1056** | **1010** |
| **External Dose** | **2.16 $\mu Gy \cdot hr^{-1}$** | **–** | **20 $\mu Sv \cdot hr^{-1}$** |

[a] **As measured for gamma radiation. In this case, the absorbed dose as measured by μGy is equivalent to the effective dose as measured by μSv.**

**– Not measured**

In general, activity in soil samples collected from the villages were within typical environmental levels associated with global fallout (Table 2), and existing external doses are considered low (Hille et al. 1998). In a separate external dosimetry study conducted by Takada et al. (1999), thermoluminescent dosimetry of building bricks obtained from several exposed locations indicated a cumulative external dose ranging from background levels to 100 cGy, with the highest external dose within Semipalatinsk City on the order of 60 cGy.

**Table 2. Summary of maximum activities in soil from villages near STS ($Bq \bullet kg^{-1}$).**

| | Dubasov 1997 | Shebell & Hutter 1997 | Yamamoto et al 1996 | Hille et al 1998 | |
|---|---|---|---|---|---|
| **Villages** | **Kurchartov** | | **Kurchartov** | **Mostik** | **Maisk** |
| **n** | **1** | **3** | **2** | **22** | **22** |
| **$^{137}Cs$** | **5.8**[a] | **Sarzhal: 72.15**[b]<br>**Kainar: 51.43**[b]<br>**Akzhar: 12.91**[b] | **28.4**[c] | **60**[d] | **68**[d] |
| **$^{60}Co$** | **<2**[a] | – | – | **<5**[d] | **<12**[d] |
| **$^{90}Sr$** | **5.2**[a] | – | – | **12**[d] | **52**[d] |
| **$^{152}Eu$** | **<10**[a] | – | – | – | – |
| **$^{154}Eu$** | **<6**[a] | – | – | – | – |
| **$^{239,240}Pu$** | **2.8**[a] | – | **3.98** [c] | – | – |
| **$^{241}Am$** | **<10**[a] | – | **0.46** [c] | **1.6**[d] | **1.3**[d] |
| **External Dose** | **0.12 $\mu Gy \bullet hr^{-1}$** | – | **0.130 $\mu Sv \bullet hr^{-1}$** | **0.101 $\mu Gy \bullet hr^{-1}$** | **0.095 $\mu Gy \bullet hr^{-1}$** |

[a] **Composite sample from 0-20 cm**

[b] **Individual sub-sample of 0-5, 5-10 and 10-15 cm**

[c] **Surface sample to 5 cm**

[d] **Surface sample to 10 cm**

There is some limited information available concerning existing internal doses experienced by the villagers. Hille et al. (1998) found that among the 769 villagers who underwent whole-body counting, all were below the minimum detectable activity threshold of 300 Bq. Bioassay results for 105 villagers revealed urinary excretion of $^{90}Sr$ from current uptake, with a maximum annual dose from $^{90}Sr$ in 1995 equal to 5 $\mu Sv$. $^{238/239}Pu$ were not detected during bioassay, possibly because the laboratory methods used were not optimal. $^{234}U$ and $^{238}U$ were found to occur in the normal range. Observed levels of $^{90}Sr$, $^{241}Am$, $^{60}Co$ and $^{134}Cs$, $^{137}Cs$ in soil were judged to be too low to pose a threat to residents from external exposures. These results suggests that no significant radiological hazards currently exist in these two villages. In addition, activity levels of $^{90}Sr$ and $^{137}Cs$ in vegetables and milk in Dolon village have been reported in the ranges of <500-6,100 $Bq/m^3$ and 300-7,900 $Bq/m^3$ for $^{90}Sr$ and $^{137}Cs$, respectively (Gastberger et al. 2000). The authors suggested that the low mean doses of $^{90}Sr$ and $^{137}Cs$ favorably limited the bioavailability of these radioisotopes. These findings reported by the above groups suggest that past cumulative external exposures greatly exceed internally-derived doses determined from current internal ingestion.

For an area the size of the STS (around 70 $km^2$), the results of the eighteen locations sampled and reported on in these papers clearly cannot be considered definitive. It appears that although the surrounding villages may currently have low external dose rates, the interior of the test site remains highly contaminated. In addition, the extent to which radionuclides may be cycling through the STS ecosystem and materials being used by villagers is not as well defined, although the studies reviewed above suggest that internal dose rates are low in the few villages examined to date. Some information exists suggesting that plants at the test site can hyperaccumlate radionuclides (Abenovna 2000). Yamamoto et al. (1996) present some evidence that the residual activity within the site is tightly bound to the soil as a result of extreme heating and melting of the soils during the tests, suggesting the potential for plant uptake to be minimal. However, Shebell and Hutter 1998 show that activity has migrated from the surface, with samples collected from a depth of 10-15 cm showing the greatest activity in many cases. Thus, it is extremely important to fully investigate the potential solubility of the residual activity, as this will not only influence uptake and cycling through the ecosystem, but also transport to ground water and other water sources.

In addition to the need for further investigation concerning transport of radionuclides through the STS ecosystem, full characterization of surface contamination is critically needed. Radionuclide contamination is known to occur as "hot spots", making fine scale characterization important (Shebell and Hutter 1998). This is especially important in light of the fact that access to the site is uncontrolled and utilized by shepherds and their herds. For example, our group had reasonably unfettered access to Chagan lake. We were able to drive up to the lake, walk to the bank, and indeed, swim in the lake if we so desired. There was an unmaintained fence around the lake, and a rusty sign warning in Russian of radioactivity. A local herder lived near the bank of the lake. Birds were using the lake as we approached. In addition to the potential exposure through ingestion of contaminated vegetation and/or livestock within the STS, significant risk may also exist from the inhalation of resuspended particulates.

There is also a need to determine to what extent the activities at the STS have impacted the biological diversity at and near the site. During meetings with ecologists from Kazakhstan State National University a claim was made that in the past, there were 100 species of higher plants at the STS, now there are less than forty. Many animal species have disappeared; for example, there were twelve species of rodents at the site, currently there are eight (Bigaliev 2000). The extent to which this has been documented, and is a result of testing at the STS or other undetermined factors, is not clear.

## On-going Characterization Efforts

There is currently a fair amount of ongoing work by Kazakh researchers to further characterize the STS and determine its biological/ecological impact. For example, a project is currently underway at the Institute of Radiation Ecology and Medicine in Semipalatinsk to enter all of the data collected over the years on meat, vegetation, water, soil and air activity into a database. The data currently only exists in unpublished hardcopy form. We also met with physicists from the National Nuclear Center (NNC) who are working on projects to further characterize the residual contamination in soil and ground water at the STS. Researchers from the Institute of Molecular Biology and Biochemistry (IMBB) are preparing a joint proposal with the NNC to conduct additional characterization of the STS and determine the impact of radionuclides on the biochemistry of representative plant species and the resulting expression at the community level.

The major difficulty in all of these efforts is that there appears to be little obvious coordination between related activities. Most of these projects are funded through the International Science and Technology Center (ISTC). The ISTC is an international organization funded by member countries, whose purpose is to provide funding to former Soviet Union weapons scientists to refocus their efforts on peaceful research. A list of project summaries and status can be found on their web site, http://www.istc.ru/. There are no fewer than 17 proposals in the ISTC database involving some aspect of radionuclide contamination at the STS when we last reviewed this website. Two projects are underway to characterize radiological and non-radiological contamination at the STS. An additional two projects have been proposed to investigate radionuclide contamination at the former plowshare sites and within the Ob'-Irtysh river system. Another project is underway to investigate ecological pathways of radionuclide migration outside of the STS, and two have been proposed to study wild animal and plant populations. Finally, a study is underway to design, develop and demonstrate a comprehensive and systematic database of the STS. While all of these projects appear to directly address the research needs at the STS, there is no obvious coordination and oversight of the work. Progress reports and results are not available through the website, and are therefore not easily available to the scientific community.

Scientists seeking ISTC funding are required to have collaborators from one of the funding countries (such as the U.S., Western Europe or Japan). This should ensure that results of the research are published in western journals and are available to western researchers. However, funding for western collaborators is not available through ISTC, requiring collaborators to have either existing research programs or develop other funding sources. This can hamper the participation of western scientists, thus reducing the potential for results of the research to find its way to western journals.

## Recommendations for Future Activities

One of the most critical questions in health effects studies of nuclear testing is: How good is the dosimetry? At the time of writing, we were not aware of any peer-reviewed publications that compare assumptions, methods, and results of dose reconstruction performed by US, Russian, and Kazakh scientists. Multinational intercomparisons of dose reconstruction efforts would further our understanding of dosimetry methods and would help minimize the potential for exposure misclassification of subjects enrolled in epidemiologic investigations.

Understanding the psychosocial impact of nuclear testing and its potential interaction in health outcome is critical. Nuclear testing at STS occurred within 160 km of a population of one million people. Historical accounts of residents who were schoolchildren before 1962 indicate that windows were blown out of their schools and that their bodies convulsed when testing occurred. People in the town of Semipalatinsk used to gather together to watch mushroom clouds form in the western skies when atmospheric testing occurred. These experiences, combined with the ecological and medical effects of radiation can have a long-lasting psychological impact on residents living near STS. Future remediation efforts should take into account the imbalance in doses reported by Russian and Kazakh scientists, as well as the cultural and political differences between Kazakhs and Russians who were involved in the testing. The development of techniques to increase access to information concerning the nuclear testing and the resulting contamination to villages adjacent to the STS would be extremely valuable to the villagers. A comparison of the risk perceptions of villagers affected by the STS and the scientists studying the health and environmental impacts of nuclear testing would also be valuable.

Additional work is also needed to fully characterize the STS with respect to contamination in all environmental media, particularly soil, vegetation, surface water and ground water. The risks to pastoralists who have uncontrolled access to the STS should be investigated, and appropriate administrative controls should be considered. The impact on biological resources should be investigated. A coordinated effort to make the results and data from these projects available to the scientific community should be a priority. A central repository (database), using a spatially-explicit geographical information system, would greatly facilitate access to STS data by researchers, collaborators, and the public. Much of the needed research is apparently being conducted through the ISTC, but timely dissemination of results through the ISTC web site and in peer-reviewed journals should lead to greater coordination of STS research.

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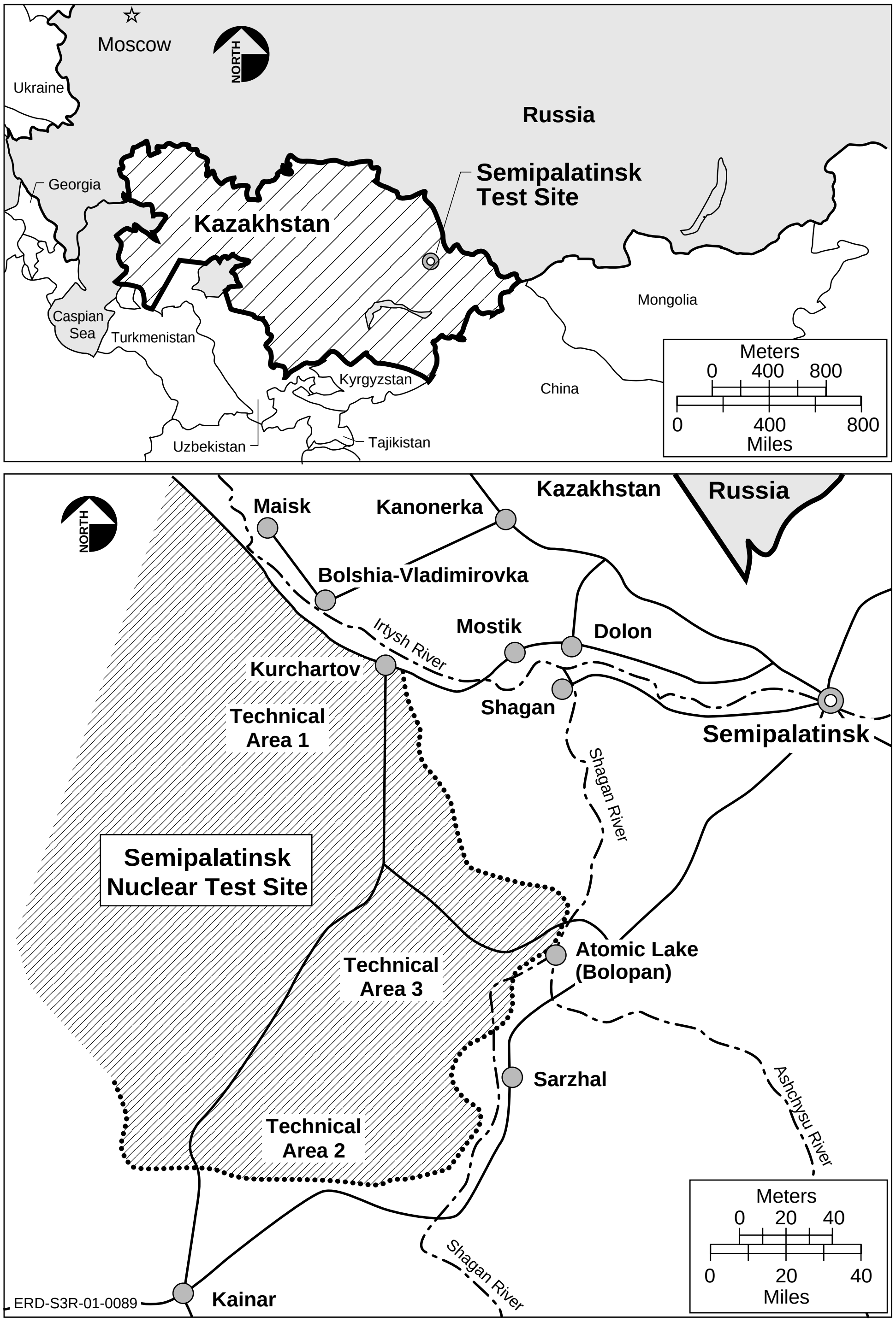


Figure 1. Location of Semipalatinsk Test Site, Kazakhstan.