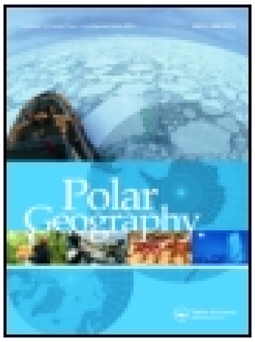

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ANTHROPOGENIC RADIOACTIVITY IN THE VICINITY OF THE BILIBINO NUCLEAR POWER STATION, CHUKOTKA, RUSSIA[1]

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Abstract: During vegetation, soil, and water sampling conducted in 1995, we were unable to confirm previous reports that the Bilibino Nuclear Power Station in the Russian Far East is a significant source of anthropogenic radioactivity to the surrounding region. A localized area of radionuclide contamination was observed for at least 400 m downstream of an effluent discharge point into a small stream, underlain by permafrost, which drains the area surrounding the power plant. It appears likely that the localized contamination observed is the result of poor drainage and the lack of adequate mixing of the discharge, rather than radionuclide discharges that are abnormally high. Radionuclides such as ^{60}Co and ^{54}Mn that are associated with nuclear energy generation also were detected on upland vegetation

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at distances of 700 m (<100 Bq/kg dry weight) to 4 km (<10 Bq/kg dry weight) from the power station, indicating that airborne releases from the power plant also contribute to the overall radionuclide burden. Total ^{137}Cs inventories in soil suggest that weapons testing fallout is still the predominant anthropogenic radionuclide source for this region and that the Bilibino Power Station currently has only a very localized influence on the surrounding area.

INTRODUCTION

The Bilibino Nuclear Power Station (BNPS) is a small (44 MW_e) nuclear power generating station located in Bilibino, Chukotka, in the Russian Far East (Fig. 1). Because of the community's remote location north of the Arctic Circle, with no overland road or ship access, four light-water-cooled, graphite-moderated reactors were put into operation between 1974 and 1976 to meet local needs for steam heat and electrical power. There have been no known significant accidents during the operating history of the power plant. However, in light of the 1986 accident at the Chernobyl' graphite-moderated reactor and, more recently, following revelations of large-scale dumping and radionuclide contamination in portions of the Russian Arctic (Yablokov et al., 1993), increased attention has been directed toward the threats posed by all potential sources of radionuclide contamination in the Russian Arctic (Office of Technology Assessment, 1995). The four units of the BNPS produce ~0.2% of the rated nuclear-generated capacity of all currently operating Russian Federation nuclear power stations (19,843 MW_e) (Office of Technology Assessment, 1995). Despite the research-reactor scale of the output of the BNPS, the plant is the closest Russian Federation civilian nuclear facility to the United States; it is located about 1300 km northwest of Nome, Alaska, and is the only civilian Russian nuclear power station in the large area of the Russian Federation that is well to the east of the Ural Mountains.

This study was initiated to follow up on reports of elevated levels of anthropogenic radionuclides in vegetation in Bilibino Rayon (Emelyanova and Neretin, 1993). These researchers reported ^{137}Cs activities of up to 9200 Bq/kg dw in pine cones of *Pinus pumila* growing 4 km from the power station in 1989-1990, suggesting that the power plant was contributing radionuclide contaminants to the surrounding area. Comparable maximum ^{137}Cs activities in vegetation at the same latitude in Alaska are currently less than 200 Bq/kg dw, and are almost entirely attributable to fallout from the atmospheric nuclear weapons testing era (Baskaran et al. 1991; Cooper et al., 1996).

The BNPS and the gold mining economy it supports in Bilibino Rayon also is of wider interest for evaluating the impact of industrial development in Arctic regions. The city of Bilibino was founded in 1958 and prospered during the Soviet era with the ready availability of heat and electricity from this small nuclear generating station, which arguably is appropriate for the size (~15,000 inhabitants) and remote geographical location of the community served. The economic basis of the community is large-scale gold mining; current gold production is 3500 kg per year. Concurrent with the abolition of the Soviet Union, new challenges also have arisen because the on-site area for storage of spent nuclear fuel is limited (Dimitrii Golobokoff, pers. comm., 1995), and declining local gold

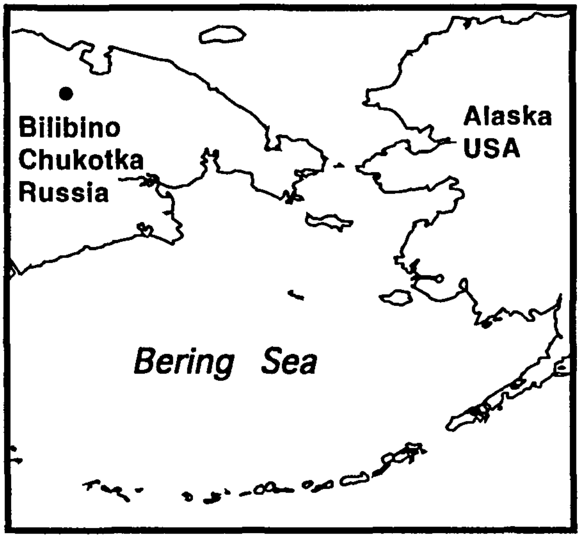

Fig. 1. General location map, Bilibino, Chukotka, Russia.

reserves suggest that the economic basis for the community could experience a period of decline, regardless of the general economic state of the Russian Federation. These economic factors have longer-term implications for the capabilities of the local, regional, and national governments to limit environmental contamination, secure nuclear waste stored on-site, and to mitigate impacts once the useful life of the BNPS has ended.

Landscape Structure and Plant Communities of the Study Area

The BNPS is situated within the northern part of the Anyuy Upland, located between the lower Kolyma River on the west and the Chaun Gulf and Anadyr' Plateau on the east. Low mountain terrain, with elevations ranging from 200 to 1000 m, prevails in the northern part of Anyuy Upland; higher elevations occur south of the Small Anyuy River. To the west and east, low mountains gradually turn into hilly plains, namely the Anyuy, Kolyma, and Chaun lowlands.

The climate of Bilibino Rayon is continental. Mean annual precipitation ranges from 100 to 200 mm. Temperatures reach a minimum in January of ~ -45° C; mean daily temperatures never exceed +20° C. Mean monthly temperatures in January are -36° C, and in July, +8° C. The mean annual air temperature is -10° C, with 170 days annually having mean daily temperatures above -10° C. Soils are generally underlain by permafrost, with the development of ice wedge polygons. The uplifted mountains of the Anyuy Upland have been eroded by a dense network of wide, deeply incised river valleys that allow low-density forests of dahurian larch (*Larix dahurica*) to penetrate northwards. Timberline is formed by larch and also by willows, including *Salix schwerinii*, *S. boganidensis*, and *Chosenia arbutifolia*. Plant communities present in the vicinity of the BNPS include the following.

(1) Tundra and *goltsy* (alpine tundra belt above the timberline) are found on steep hill slopes. This plant community is dominated by arctic dwarf shrubs, including blueberry (*Vaccinium uliginosum*), lingonberry (*Vaccinium vitis-idaea*), marsh tea (*Ledum decumbens*), wineberry (*Empetrum subholarcticum*), *Diapensia obovata*, *Dryas* spp., and lichens.

(2) A band of *Pinus pumila*—mountain (Siberian stone) pine, occurs at an elevation of 650-850 m. Mountain pine thickets with lichens (*Stereocaulon paschale*) are found on stony substrates, as opposed to steep slopes with better soils, which are dominated by dwarf shrubs. These shrubs include birches such as *Betula middendorffii* and *B. exilis*. In disturbed areas with good drainage, annuals such as foxtail grass (*Alopecurus* spp.) and arctic bent (*Arctagrostis* spp.) are common.

(3) A forest belt occupies elevations from 300 to 650 m. The most widespread association is larch forest dominated by *Larix dahurica*, with an understory of dwarf birch and willows (including *Salix kolymensis*, *S. glauca*, and *S. hastata*) and moss cover dominated by *Aulacomnium turgidum* and *Ptilidium ciliare*.

(4) Riparian communities exist in river valleys, including sedge-cotton grass, mosses, and reed-grass (*Calamogrostis*). Hummocks provide microrelief, particularly in sedge-cotton grass communities dominated by *Carex aquatilis*, *Eriophorum polystachion*, and *E. vaginatum*. Stands of willow (*Populus suaveolens*) and *Chosenia* are found on recent alluvium close to water level.

Power Plant Design

The BNPS reactors have a unique design, designated EPG-6, not used in any other Russian civilian power plant (Office of Technology Assessment, 1995). The reactor fuel is ^{235}U enriched to 3 to 3.3%. The primary cooling system has six separate circulation loops, and in addition to generating electricity, uses heat exchange to generate hot water for a separate closed system (Dimitrii Golobokoff, pers. comm., 1995), which provides heat to the town of Bilibino, approximately 5 km from the BNPS.

MATERIAL AND METHODS

Surveys for gamma radiation were conducted initially using hand-held portable scintillation (NaI) detectors (BICRON Survey MX, Bicron Crop., Newbury, Ohio) to establish the levels of background radiation and to identify areas deviating from background. Dose equivalent rates were measured using a tissue-equivalent organic scintillator (Bicron Micro REM). Following these initial surveys, vegetation, soil, and water samples were collected in Bilibino Rayon over the period 10-12 August, 1995 at several locations ranging from 100 to 4000 m from the BNPS reactor building (Fig. 2). In addition to samples of specific plants, two soil cores (172 cm^2) were collected to evaluate total deposition inventories in the Bilibino area. The soil cores were sectioned in the field, in 1-cm increments to a depth of 4 cm, then in 2-cm increments to a depth of 20 cm, and in 4-cm increments below 20 cm depth. All samples were returned to Oak Ridge National Laboratory and sealed in polyethylene Marinelli beakers and other similar containers

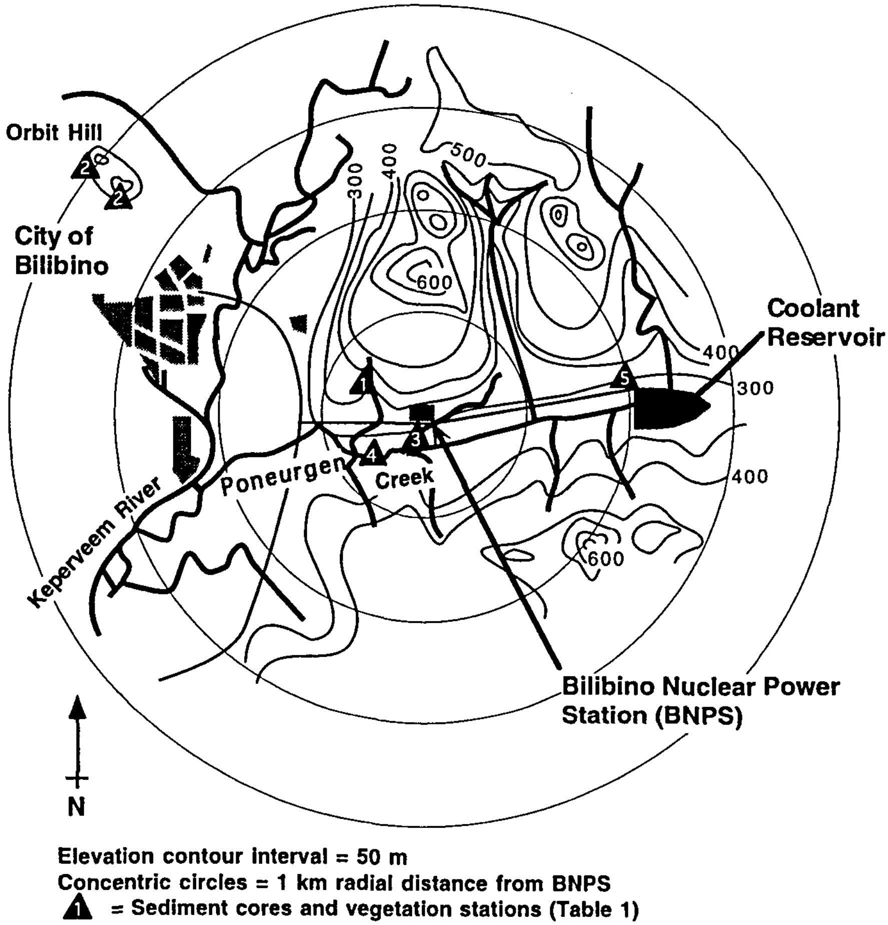

Fig. 2. Sampling locations relative to the Bilibino Nuclear Power Station.

suitable for direct counting by gamma spectrometry. Radioactivity was assayed using low-background, high-resolution, germanium gamma-ray detectors equipped with a Canberra Genie personal computer system programmed to record gamma spectra in 4096 channels. Calibration of the detectors was performed using standards obtained from the U.S. National Institute of Standards and Technology (NIST). Background corrections were performed and appropriate control samples were analyzed to verify detector performance. Following gamma spectrometry, soil and vegetation samples were dried to a constant weight in an oven at 60° C.

RESULTS

Through the use of hand-held scintillation counters, the background radiation level within the town of Bilibino was established to be 2 μrem/hr^{-1} on 10 August 1995. Radiation levels were monitored in a transect between a 100-m perimeter

TABLE 1

Radioactivity in Vegetation Samples Collected in Bilibino Rayon, August 1995[a]

Sample	Date, 1995	Sample dry weight, g	^{137}Cs (Bq/kg) ± 1σ	^{60}Co (Bq/kg) ± 1σ	^{7}Be (Bq/kg) ± 1σ	^{40}K (Bq/kg) ± 1σ	^{54}Mn (Bq/kg) ± 1σ
Core Site No. 1, 700 m northwest of BNPS (Site 1, Fig. 2)							
Lichen, unidentified	6 August	146.22	49.2 ± 1.0	71.5 ± 1.4	146.8 ± 8.9	101.8 ± 7.7	11.3 ± 0.8
Equisetum spp.	10 August	4.34	2.8 ± 3.6	5.7 ± 3.1	75.0 ± 42.9	1421.2 ± 88.0	n.d.[b]
Mixed mosses, 100 m uphill from core site (0.25 m^2)	10 August	39.01	25.8 ± 1.7	64.7 ± 2.5	279.8 ± 16.3	145.1 ± 21.9	9.4 ± 1.9
Orbit Hill (Site, 2, Fig. 2)							
Mushrooms, unidentified species #1	6 August	50.90	60.5 ± 1.5	n.d.	45.7 ± 14.8	756.7 ± 22.0	n.d.
Mushrooms, unidentified species #2	6 August	51.25	147.9 ± 2.9	n.d.	n.d.	1128.4 ± 34.9	n.d.
Mushrooms, unidentified species #3, under birch	6 August	28.76	41.1 ± 1.8	n.d.	n.d.	951.2 ± 32.6	n.d.
Mixed lichens from top of hill (0.25 m^2)	12 August	142.48	184.6 ± 1.5	2.3 ± 0.4	96.9 ± 8.0	71.9 ± 6.1	n.d.
Larix dahurica (Larch) cones from top of hill	12 August	90.46	2.1 ± 0.5	n.d.	195.1 ± 7.7	58.1 ± 9.5	n.d.
Pinus pumila, needles from top of hill	12 August	8.13	n.d.	n.d.	95.6 ± 23.1	219.8 ± 35.1	n.d.
Pinus pumila, cones from top of hill (crushed)	12 August	182.22	7.8 ± 0.4	n.d.	n.d.	158.6 ± 6.4	n.d.
Eriophorum polystachion, from bottom of hill	12 August	62.12	5.1 ± 0.9	n.d.	185.2 ± 10.8	511.6 ± 18.2	n.d.

	"Technological Water" Outfall, 100 m south of BNPS (Site 3, Fig. 2)						
Equisetum spp.	10 August	26.67	37.9 ± 3.2	524.4 ± 7.2	187.3 ± 24.4	457.8 ± 35.1	136.2 ± 4.7
Salix spp., leaves	10 August	9.16	n.d.	79.6 ± 3.6	77.4 ± 22.4	606.7 ± 40.8	10.0 ± 2.2
Grass	10 August	56.29	50.0 ± 2.3	882.1 ± 8.0	47.5 ± 15.1	167.0 ± 20.0	17.2 ± 2.4
Umbelliferae, unidentified species	10 August	7.62	1440.7 ± 40.7	23,362.9 ± 358.9	n.d.	1211.5 ± 83.1	3135.3 ± 141.2
	River bottom/floodplain, 400-500 m southwest of BNPS (Site 4, Fig. 2)						
Salix spp., leaves	10 August	99.45	1.3 ± 0.4	17.1 ± 1.1	202.8 ± 6.7	305.4 ± 11.8	4.8 ± 0.6
Salix spp., leaves	10 August	79.41	0.5 ± 0.6	29.0 ± 1.4	146.3 ± 11.1	366.7 ± 15.2	3.9 ± 1.1
Betula spp., leaves	10 August	77.00	1.9 ± 0.5	12.7 ± 1.0	103.8 ± 8.3	79.8 ± 10.9	2.9 ± 0.8
Aquatic macrophyte (unidentified)	10 August	26.92	n.d.	n.d.	105.8 ± 17.0	749.9 ± 36.3	n.d.
Ptarmigan scat	10 August	129.23	4.9 ± 0.5	93.9 ± 1.5	109.9 ± 5.4	11.6 ± 0.7	
	Dam Site, 2 km east of BNPS (Site 5, Fig. 2)						
Epilobium angustifolium (fireweed)	9 August	40.03	n.d.	n.d.	146.0 ± 11.7	540.7 ± 21.6	n.d.
Larix dahurica (larch) cones	9 August	9.56	n.d.	n.d.	126.4 ± 20.9	3.1 ± 22.8	n.d.
Mixed mosses (0.25 m^2)	9 August	48.00	31.3 ± 1.4	3.5 ± 1.1	218.9 ± 14.0	171.9 ± 17.9	0.9 ± 0.6
Dried grass	9 August	8.16	n.d.	4.6 ± 2.1	429.8 ± 35.8	71.4 ± 31.1	n.d.
	Other locations						
Lichen from 0-2 cm in gravel, 500 m north of BNPS	10 August	324.66	117.4 ± 0.8	14.7 ± 0.4	48.7 ± 3.2	179.4 ± 4.2	0.3 ± 0.2
Larix dahurica, cones, 100 m north of BNPS	10 August	14.14	n.d.	79.9 ± 4.5	89.2 ± 20.7	194.9 ± 33.8	11.1 ± 2.0

[a]No significant levels of any other gamma-emitting radionuclides were detected.
[b]n.d. = not detected.

from the reactor building to the BNPS cooling-water reservoir, approximately 2000 m to the east (Fig. 2). Gamma radiation levels at the BNPS main entrance were 5 μrem/hr, increasing to 20 μrem/hr directly south of the reactor building, at about 100 m distance. At the time of the survey, two of the reactors were off-line, and two were operating (Dimitrii Golobokoff, pers. comm., 1995). Proceeding east from the BNPS, gamma radiation levels returned to background within 300 m. The coolant reservoir, with a storage area of 3.5×10^6 m^2, is used only for cooling water supply and not for effluent discharge (Dimitrii Golobokoff, pers. comm., 1995); no above-background radiation was detected anywhere in the vicinity of the reservoir. The only other location anywhere in the Bilibino district where above-background radiation levels were detected using hand-held instruments during the survey was an effluent outfall located south of the power plant (11 August). Radiation levels in the immediate vicinity of the outfall were two to three orders of magnitude higher, in the range of 0.5 to 1.5 mrem/hr. The outfall discharge flowed into Poneurgen Creek, the nearest surface stream to the BNPS (Fig. 2). No extensive survey was undertaken to define the area of radionuclide contamination, but a shift from background (2-3 μrem/hr) to approximately three times background (6 μrem/hr) was observed in floodplain soils approximately 400 m from the BNPS in downstream portions of Poneurgen Creek.

Vegetation, soil, and water sampling was planned in conjunction with the findings from these radiation surveys. Vegetation was sampled in several areas, including the floodplain of Poneurgen Creek downstream from the BNPS, at the effluent outfall, at the reservoir, and in two wooded areas 700 m and 4000 m from the BNPS (Fig. 2; Table 1). Two soil cores were obtained, one about 700 m from the BNPS (Fig. 3), and the other from floodplain soils adjacent to Poneurgen Creek and approximately 400 m downstream from the BNPS (Fig. 4). This latter soil core was collected at the location where hand-held meters indicated a transition to above-background radiation. Several liters of water also was collected at the effluent discharge point, approximately 100 m south of the BNPS, and several anthropogenic radionuclides were detected (Table 2).

Anthropogenic radionuclides—including ^{137}Cs, ^{60}Co, and ^{54}Mn—were detected in some of the soils and vegetation samples. However, the higher activity observed near the effluent outfall was the only instance in which total gamma radiation clearly exceeded the ambient background (Table 1).

DISCUSSION

During this work, we were unable to verify the relatively high radioactive contamination levels that previously had been reported (Emelyanova and Neretin, 1993) several km from the BNPS. For example, cones of *Pinus pumila* collected at a distance of 4 km from the power plant had ^{137}Cs activities of 7.8 Bq/kg dry weight (Table 1), less than 1% of the ^{137}Cs activities in pine cones at the same location in the previous study, reported to be as high as 9200 Bq/kg dry weight. The analytical methods employed in the previous study were destructive of the samples collected, so it is impossible to directly evaluate potential analytical errors in the previous work. Evidence remains for radioactivity of local anthropogenic origin, because of the presence of reactor neutron activation products

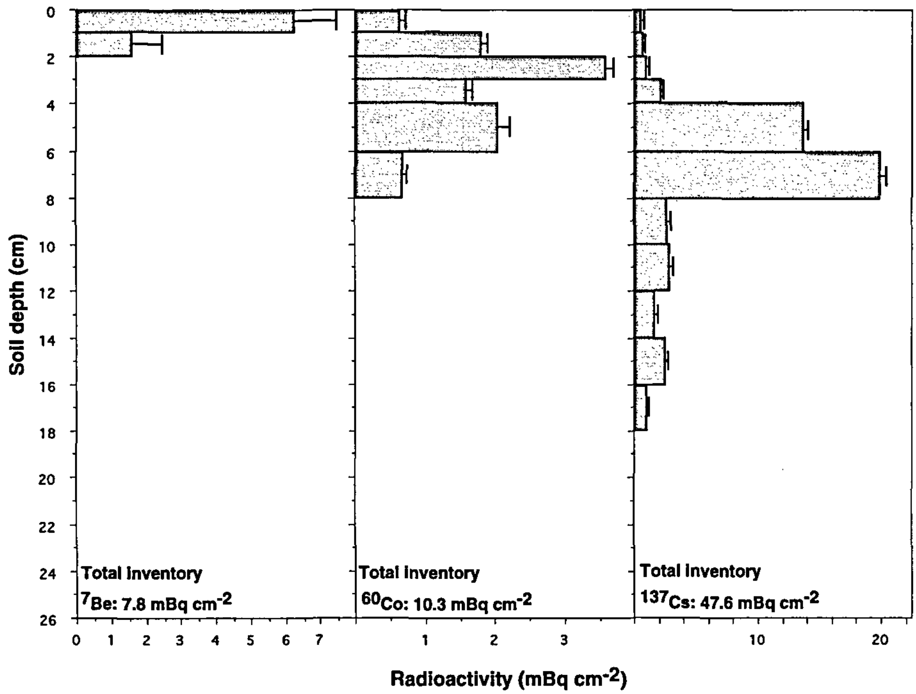

Fig. 3. Radioactivity (± SE) in soil core collected at upland site, 700 m northwest of Bilibino Nuclear Power Station, 10 August 1995. Total inventories given are integrated sums per cm of core depth for each radioisotope.

such as ^{54}Mn, ^{60}Co, and ^{51}Cr, particularly in plants and floodplain soils downstream from the effluent discharge zone (Table 1, Fig. 4) and in the water discharge itself (Table 2). Gross gamma activity in the water discharge (Table 2), however, was below the limits in force at the BNPS (11.1 Bq/L; Dimitrii Golobokoff, pers. comm., 1995). It is noteworthy that except in areas immediately adjacent to the effluent outfall at the power plant, gross gamma activity of natural origin (e.g., ^{7}Be and ^{40}K) in plant samples exceeded that from anthropogenic sources (Table 1).

In addition to waterborne discharges of nuclear products, there also must be some small degree of atmospheric deposition originating from the power station because of the presence of trace to modest quantities of ^{54}Mn and ^{60}Co on surface vegetation in upland areas located up to 4 km from the BNPS (Table 1, Fig. 3). The detection of low levels of atmospherically transported reactor products is consistent with monitoring data from other nuclear generating stations. For example, Ikäheimonen et al. (1995) reported detection of ^{60}Co and ^{54}Mn in a few deposition samples collected on a monthly basis during 1991-1992 adjacent to the power plant at Loviisa, Finland, where there are two 445 MW$_e$ pressurized-water reactors. Deposition rates in those months when reactor products were detected were less than 0.1 mBq/cm^2, however, suggesting that atmospheric deposition from the BNPS may be somewhat higher to account for a total ^{60}Co inventory of 10.3 mBq/cm^2 at a distance of 700 m from the power plant (Fig. 3). The total

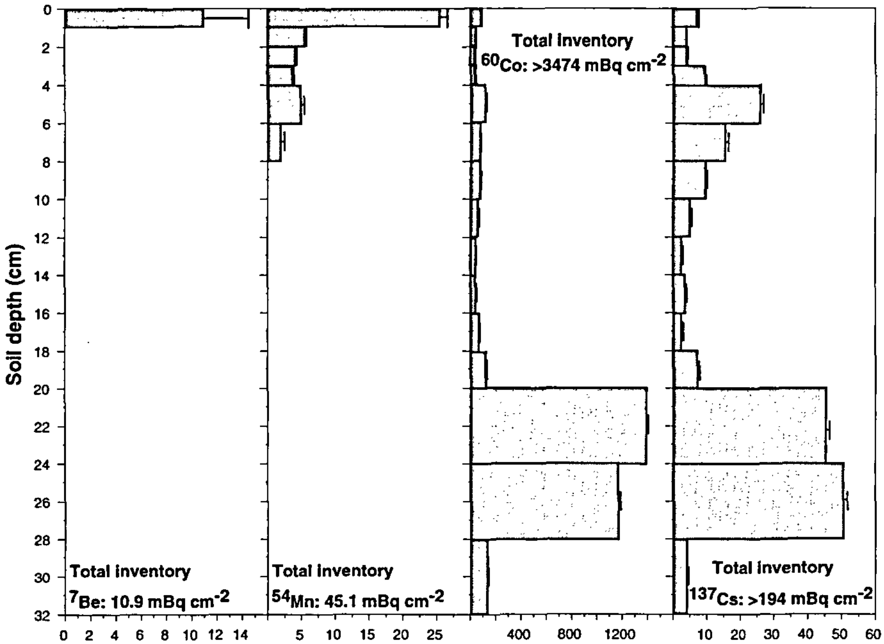

Fig. 4. Radioactivity (± SE) in soil core collected in Poneurgen Creek floodplain, 400 m downstream from effluent discharge point, 10 August 1995. Total inventories given are integrated sums per cm of core depth for each radioisotope.

TABLE 2

Radioisotope Concentrations in "Technological Water"[a] at BNPS Effluent Outfall, 10 August 1995

Isotope (half-life)	Concentration (Bq/L) $\pm 1\sigma$
^{51}Cr ($t_{1/2}$ = 28 days)	3.27 ± 0.67
^{60}Co ($t_{1/2}$ = 5.3 years)	0.47 ± 0.02
^{54}Mn ($t_{1/2}$ = 312 days)	0.25 ± 0.02

[a]Refers to that portion of the released liquid waste stream that is discharged into the environment and contributes to localized contamination.

inventory of ^{137}Cs (47.6 mBq/cm^2) is lower than the range observed in a series of total radiocesium inventories determined at Imnavait Creek, Alaska (68° 37′ N, 149° 17′ W) in 1990 (116 mBq/cm^2 ± 28.7 S.D., n = 12), as well as six more widely spaced cores collected between Imnavait Creek and the Arctic Ocean coast at

Prudhoe Bay, Alaska (53 to 142 mBq/cm^2) in 1991 (Cooper et al., 1995). These Alaskan cores were collected far from any source except 1960s-derived bomb fallout, and contain at most very small contributions from the Chernobyl' accident (Baskaran et al., 1991). This indicates that even in the immediate vicinity of the BNPS, atmospherically derived fallout of radionuclides from weapons testing during the early Cold War period is the primary source of the anthropogenic radionuclide burden in soils.

If it is true that the radiocobalt present in Bilibino soils is derived only from power plant operations, the disappearance of radiocobalt from the BNPS upland core below 8 cm depth (Fig. 3) suggests new radionuclide accumulations starting at some point after 1974, when the plant began operating. Another line of evidence that the impact of the power plant is recorded in nearby soils is the sharp decrease in radiocesium at the same depth, 8 cm. The disappearance of radiocobalt below 8 cm depth, while ^{137}Cs remains present from 10 to 18 cm, suggests that this radiocesium may be a remnant of atmospheric deposition from bomb fallout only. An alternative explanation, however, is that radiocobalt that has penetrated beneath 8 cm depth has decayed away. This possibility can be evaluated by considering the minimum detectable activity for the 2-cm increment of soil where ^{60}Co was last detected, from 6 to 8 cm. Under the counting conditions employed, the minimum detectable ^{60}Co activity for the 6-8 cm depth was 26 mBq. For this 2-cm core increment, one-half of the area of the 172 cm^2 core was counted (i.e., 84 cm^2), or 172 cm^3 (for 1-cm core increments, the entire 172 cm^3 was counted). Therefore, the minimum radiocobalt activity that could be detected (26 mBq $\div$ 84 cm^2) was 0.30 mBq/cm^2 for the entire 2-cm increment. This is about one-half the radiocobalt activity actually detected in the 6-8-cm core interval (0.66 mBq/cm^2 for the 2-cm-deep interval). The time period required to reduce the activity observed at 6-8 cm to the detection limit therefore would be slightly longer than the half-life of ^{60}Co (5.3 yr), about 6 years. This indicates a penetration rate for ^{60}Co at this depth of ~0.3 cm/yr, based on the 2-cm distance between the midpoint of the last depth increment where ^{60}Co was detected and the midpoint of the 2-cm increment directly below.

A similar penetration analysis can be performed for the last core increment where ^{137}Cs was detected, 16-18 cm (Fig. 3). The minimum detectable activity for ^{137}Cs was 67.0 mBq under the counting conditions that we employed. Therefore ~4.1 years would be required for the total activity detected in the 2-cm increment at 16-18 cm (73.6 mBq) to decay to this minimum detectable activity, based upon the half-life of ^{137}Cs (30.2 yr). Thus the rate of ^{137}Cs penetration between the midpoints of these two core segments (2 cm apart) can be estimated to be 0.5 cm/yr.

Using the penetration-rate estimate for radiocobalt (0.3 cm/yr), the depth of the earliest detected appearance of ^{60}Co (at 6-8 cm depth; midpoint of 7 cm used for calculation) can be dated to deposition around 1972, relatively close to the initiation of power plant operations at Bilibino in 1974. Using the penetration rate estimate for radiocesium (0.5 cm/yr), the depth of the earliest appearance of ^{137}Cs at 17 cm can be dated to deposition around 1961, which is in reasonable agreement with the timing of large-scale deposition of radiocesium following atmospheric nuclear weapons testing. Nevertheless, this penetration analysis must be only approximately correct. If the peak in radiocesium at 6-8 cm depth (Fig. 3) reflects added contributions at the time the power plant began operations, and coincides with the appearance of radiocobalt in the soil core at 6-8 cm, then use of a 0.5 cm/yr radiocesium penetration rate suggests the contributions of airborne radionuclides from the BNPS began about 1980, rather than 1972, as indicated by the penetration estimate for radiocobalt. Given the low levels of ^{60}Co in the core, close to detection limits at 6- to 8-cm depth, and these other considerations, we are unable to categorically date the appearance of ^{60}Co and the ^{137}Cs maximum (at 6-8 cm) as corresponding to the initiation of power plant operations in Bilibino in 1974, based upon available data.

The second core, collected in the Poneurgen Creek floodplain, did not yield a complete inventory because anthropogenic radionuclides still were present at the bottom of the core (Fig. 4). Total inventories to a depth of 28-32 cm far exceeded that observed in the upland tundra core, particularly for ^{60}Co; radiocesium and radiocobalt reached activity maxima at a depth of 20-28 cm (Fig. 4).

The presence of ^{54}Mn only in the top 8 cm of the core suggests that the more deeply buried ^{60}Co radioactivity maxima did not result from releases within the past several years, given the half-life of ^{54}Mn (312 days). It seems reasonable to assume that any ^{54}Mn associated with the discharge of the deeply buried ^{60}Co maxima would have decayed away, and that ^{54}Mn at the surface corresponds to recent deposition. A natural logarithmic plot of ^{54}Mn activity versus depth below the top 1-cm interval (Fig. 5) yields a regression line ($r^2 = 0.93$) described by the equation depth (cm) = 7.84 - 2.40 × ln ^{54}Mn (mBq/g dry weight). Expressed in the reciprocal form, a sediment accumulation coefficient, with units of cm^{-1}, can be derived. This sediment accumulation coefficient (slope) is 0.389 cm^{-1}. Division of the specific activity for ^{54}Mn (0.811/yr) by this slope yields a sediment accumulation rate for the core of ~2.1 cm/yr. Activity was detected in the surface 1-cm core increment (Fig. 5), associated with grass growing in the floodplain rather than with mineral soil. If the ^{54}Mn activity detected in this grass on a per cm basis is included in the regression, the regression coefficient (r^2) is reduced to 0.86 and the estimated sedimentation rate decreases to 1.8 cm/yr.

At the time this core was collected, 21 years had elapsed since the first reactor at Bilibino went critical. If we assume constant sedimentation and similar sedimentation behavior patterns for ^{60}Co and ^{137}Cs, the core would have had to have been 44 cm deep (based upon the 2.1 cm/yr accumulation rate) before reaching sediments deposited before the BNPS became operational. If these assumptions about constant, similar sedimentation patterns are correct, it is possible to estimate the date of the large pulse of ^{60}Co at 20- to 28-cm depth (Fig. 3) as occurring in about 1985-1987. The large pulse may have been the result of redeposition and sediment focusing following scouring of poorly drained upstream areas during a large snowmelt or flooding event. However, given the apparent decadal period that the radiocobalt had been buried relative to the half-life of ^{60}Co (5.3 y), the order of magnitude of increase in ^{60}Co at 20-28 cm suggests that there may have been a significant release of radiocobalt in the mid-1980s.

The portion of the released liquid waste stream that is discharged into the environment and has contributed to this localized contamination is referred to as "technological water" (Dimitrii Golobokoff, pers. comm., 1995). This waste stream

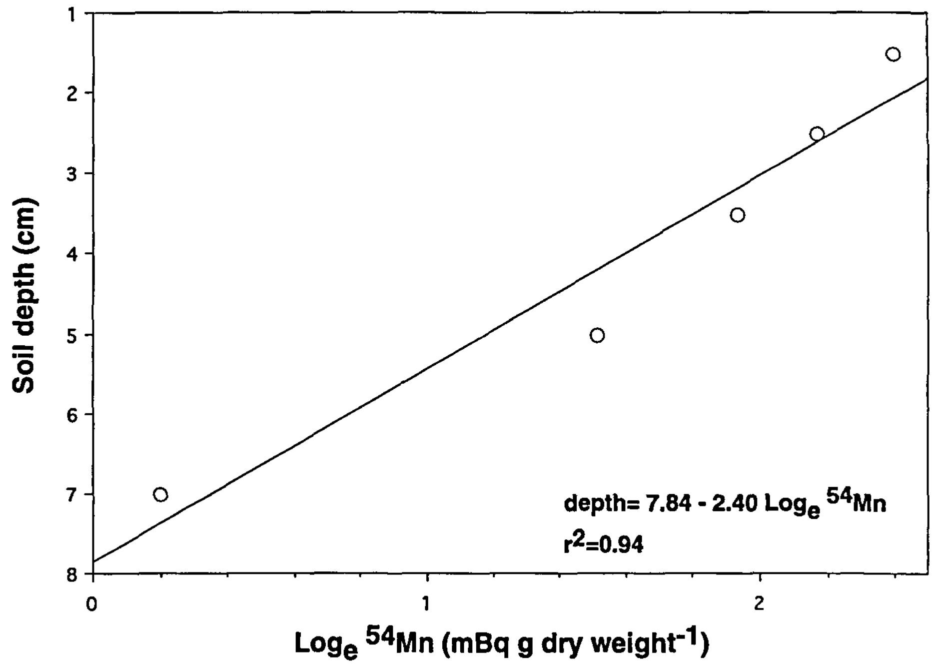

Fig. 5. Natural logarithm plot of activities of ^{54}Mn relative to depth for core that was plotted in Figure 4.

originates from a variety of unit treatment processes, with the largest contribution coming from condensate from waste evaporation. Condensate separated during evaporation is processed on a batch basis and is analyzed by gamma spectroscopy prior to being discharged (Dimitrii Golobokoff, pers. comm., 1995). Once released from the condensate storage tank, the waste stream mixes with a continuous flow of dilution water. Although the radioactive component of this waste stream (that portion that originates from the waste evaporation process) is processed on a batch basis, the continuous nature of the technological water discharge effectively represents a continuous discharge of radioactive effluent.

Assuming that these concentrations represent typical discharges associated with normal reactor operations (i.e., planned releases in accordance with BNPS internal operating procedures), an estimate of the annual release of these isotopes from the BNPS can be calculated. Based upon measurements made by BNPS technical staff, a volumetric discharge of 3.40×10^8 L/yr is estimated to be the total flow associated with the technological water discharge (~10 L/s). Through use of the concentrations of each isotope measured (Table 2), which we assume to be representative, the total quantity of each radioactive species discharged on an annual basis can be estimated to be 1.11 GBq for ^{51}Cr, 0.16 GBq for ^{60}Co, and 0.08 GBq for ^{54}Mn.

A comparison between these estimates of annual liquid radioactive discharge from the BNPS and that from several U.S. nuclear power generating plants, using data from 1992, is provided in Table 3. There are several differences between

TABLE 3

Total Radionuclide Waterborne Discharges, Selected Nuclear Power Stations, 1992[a]

Plant	Isotope	1992 annual release, GBq/yr	Rated generating capacity, MW_E	Volume of water dilution, 10^6 m^3	Radionuclide burden in discharge, GBq/10^6 m^3
South Texas Unit 1	^{51}Cr	1.89	1251	29.7	0.06
	^{60}Co	14.58			0.49
	^{54}Mn	1.99			0.07
Browns Ferry Unit 2	^{51}Cr	5.66	1065	173.0	0.03
	^{60}Co	5.03			0.03
	^{54}Mn	1.70			0.01
Clinton Unit 1	^{51}Cr	0.06	960	0.118	0.51
	^{60}Co	0.37			3.13
	^{54}Mn	0.15			1.27
Dresden Unit 2, 3	^{51}Cr	—	772	12.5	—
	^{60}Co	0.40			0.03
	^{54}Mn	0.18			0.01
Big Rock Point Unit 1	^{51}Cr	0.08	63	65.1	0.01
	^{60}Co	1.67			0.02
	^{54}Mn	2.50			0.03
Bilibino Units 1, 2, 3, 4	^{51}Cr	1.11 (1995 est.)	44	0.34	3.26
	^{60}Co	0.16			0.47
	^{54}Mn	0.08			0.23

[a]Release data for U.S. plants from Nuclear Regulatory Commission (1995). Bilibino estimates based upon this study, using 1995 measurements.

discharge processes at BNPS and at U.S. power stations. For example, the majority of radioactive liquid wastes generated at U.S. nuclear reactors are processed and discharged on a batch basis. Total gamma isotopic activity concentrations are determined for each batch of liquid effluent prior to release. The total activity of a released batch is determined by summing the concentration of each radionuclide and multiplying by the total volume discharged. The total activity of each batch released during the year then is summed to determine the annual release of each radioactive species. For the purpose of this comparison, the isotopic discharge estimates for U.S. power plants reflect only those gamma-emitting isotopes that were detected in the BNPS technological water discharge. U.S. plants typically discharge, analyze, and record data for a larger number of beta- and gamma-emitting isotopes.

Many factors influence the quantity of radioactive material released during nuclear power generation, including the condition of the fuel, primary system integrity, effluent and radioactive waste treatment systems, the extent to which these systems are used, and the length of time and corresponding power level at which the plant is operated. These factors, together with the unique reactor design of the BNPS power plant, make it difficult to directly compare the performance of the Bilibino plant with respect to releases of radioactive materials.

CONCLUSIONS

Even after these limitations are recognized and the high degree of variability among individual power plants is considered, it appears that the quantity of radioactive effluents released from the BNPS is roughly comparable to that released from U.S. nuclear plants. The BNPS may have a higher release of radioactive effluent relative to electricity generated, but there are no directly comparable, small-scale civilian reactors that would justify a conclusion that the BNPS generates unexpectedly high radioactive contamination.

The primary reason for the accumulation of radioactive material in the discharge zone is hydrology. The area currently receiving the discharge is underlain by permafrost and is subject to poor drainage and low stream flow. Poneurgen Creek, the initial discharge stream, is only a few meters in width. By comparison, most nuclear plants discharge effluent through diffusers into large bodies of moving water that prevent radioactive material from concentrating within localized areas of the environment. The BNPS also is an unusual case among nuclear-power-generating facilities because of its construction in a region with permafrost. Movement of radionuclides in local soils, whether originating from the outfall or from atmospheric deposition, are no doubt affected by the presence of permafrost and the seasonal changes in active-layer depth.

In Russia, there currently is little or no funding for capital improvements, so further expenditures to reduce the quantities of radioactive materials released from the plant are unlikely. A more appropriate and cost effective solution would be to restrict access to the contaminated areas that we sampled, which currently are neither fenced nor posted.

Farther downstream from the power plant, the radioactive discharge from the plant is quickly diluted. Water flowing downstream in Poneurgen Creek enters the Keperveem River, then the Malyy Anyuy River, and eventually the Kolyma River, near its delta. The water discharge from the Kolyma into the East Siberian Sea is estimated to be 102 km^3/yr (Aagaard and Carmack, 1989). Based upon our limited sampling effort, and assuming that it was representative, our estimate of an annual waterborne discharge of 0.16 GBq of ^{60}Co would result in a maximum waterborne burden of ^{60}Co in the Kolyma estuary of 0.0015 Bq/m^3, neglecting any ^{60}Co deposited in river sediments downstream from the power plant. The other radionuclides detected in the effluent sample we collected—^{51}Cr and ^{54}Mn—were neglected in this marine impact estimate because of their shorter half-lives, 28 days and 312 days, respectively. Although this analysis is speculative because of the limited effluent sampling, it may help put into perspective the current regional impact of the power plant. The maximum potential burden of

^{60}Co estimated to enter the East Siberian Sea is several orders of magnitude below the relatively low ^{137}Cs burdens (0.28 Bq/m^3 ± 0.04 SD, $n = 22$; unpubl. data, 1995) that have been measured in East Siberian Sea waters. No ^{60}Co has been detected in these East Siberian Sea water samples and the detectable radiocesium burdens are almost certainly a result of atmospheric bomb fallout only. Although it is believed that ocean currents near the Kolyma delta may be hydrographically linked to the Siberian Coastal Current flowing eastward toward Alaska (Johnson et al., 1995), this sampling indicates that the BNPS has no current significant radiological impact beyond the immediate vicinity of the power plant effluent discharge zone.

Future research might include more technical evaluations of the working safety of the power plant and cooling system, as well as security issues. Although various internationally funded programs are available for improving nuclear power operations, safety, and monitoring in the countries of the former Soviet Union, no significant funds from sources outside of Russia have been expended at the Bilibino facility to this date (Office of Technology Assessment, 1995). Despite its small electrical generating capacity, the unique reactor design and the relative proximity of the BNPS to the international boundary with the United States suggest that additional international exchange and study of the current and potential impact of the power station on the Bilibino area would be beneficial.

LITERATURE

Aagaard, K. and E. C. Carmack. "The role of sea ice and other fresh water in the Arctic circulation," *Jour. of Geophys. Res.*, Vol. 94, 1989, pp. 14,485-14,498.

Baskaran, M., J. J. Kelley, A. S. Naidu, and D. F. Holleman. "Environmental radiocesium in subarctic and arctic Alaska following Chernobyl," *Arctic*, Vol. 44, 1991, pp. 346-350.

Cooper, L. W., J. M. Grebmeier, I. L. Larsen, C. Solis, and C. R. Olsen. "Evidence for re-distribution of cesium-137 in Alaskan tundra, lake and marine sediments," *The Science of the Total Environment*, Nos. 160/161, 1995, pp. 295-306.

Cooper, L. W., I. L. Larsen, C. Solis, J. M. Grebmeier, C. R. Olsen, D. K. Solomon, and R. B. Cook. "Isotopic tracers for evaluating hydrological processes," in: J. F. Reynolds and J. D. Tenhunen, eds., *Landscape Function: Implications for Ecosystem Response to Disturbance.* Berlin: Springer-Verlag, 1996, pp. 165-182.

Emelyanova, L. and L. N. Neretin. "Accumulation of ^{137}Cs and ^{90}Sr in food chains of ecosystems in the Bilibino Atomic Power Station Area," in: *International Symposium on the Ecological Effects of Arctic Airborne Contaminants, Reykjavik.* Hanover, NH: U.S. Cold Regions Research and Engineering Laboratory Special Report 93-23 (errata), 1993.

Ikäheimonen, T. K., S. Klemola, E. Ilus, and K.-L. Sjöblom. *Monitoring of Radionuclides in the Vicinities of Finnish Nuclear Power Plants in 1991-1992.* Helsinki: Finnish Centre for Radiation and Nuclear Safety, STUK-A121, 1995.

Johnson, M., A. Proshutinsky, and J. Groves. "High resolution modeling and remote sensing of the East Siberian and Alaskan shelf," in: J. Morgan and L. Codispoti, *Department of Defense Arctic Nuclear Waste Assessment Program, FY's 1993-1994.* Arlington, VA: Office of Naval Research, Report No. 322-95-5, 1995, 126-129.

Office of Technology Assessment. *Nuclear Wastes in the Arctic: An Analysis of Arctic and Other Regional Impacts from Soviet Nuclear Contamination*, Washington, DC: U.S. Government Printing Office, OTA-ENV-623, 1995.

U.S. Nuclear Regulatory Commission. *Annual Report on Radioactive Materials Released from Nuclear Power Plants, 1992.* Washington, DC: U.S. Government Printing Office, NUREG/CR-2907 BNL-NUREG-51581, 1995.

Yablokov, A. V., V. K. Karasev, V. M. Rumyantsev, M. Y. Kokeyev, O. I. Petrov, V. N. Lystsov, A. F. Yemelyankenkov, and P. M. Rubtsov. *Facts and Problems Related to Radioactive Waste Disposal in Seas Adjacent to the Territory of the Russian Federation.* Moscow: Office of the President of the Russian Federation, 1993 (English-language version translated by Paul Gallager and Elena Bloomstein and published by Small World Publishers, Inc., Albuquerque, NM.)