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Environmental Radiocesium in Subarctic and Arctic Alaska Following Chernobyl

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ABSTRACT. Radiocesium (^{134}Cs and ^{137}Cs) concentrations were measured in soil, plant and wildlife samples from subarctic to arctic Alaska. Concentrations of ^{137}Cs ranged from below detectable or low levels in whale and fish samples to as high as 242 Bq/kg in lichen. For all potential human food items, the radiocesium concentrations measured in this study were below accepted permissible levels for human consumption. Chernobyl-derived radiocesium concentrations ranged from below detectable or low levels in all arctic samples (soil, sediment, lichen, whale, fish and caribou) to 32 Bq/kg in subarctic moss. Therefore the distribution and subsequent deposition of Chernobyl-derived radiocesium appears to be variable but decreasing significantly from the Subarctic (Fairbanks) to the Arctic. The present data support the suggestion that Chernobyl-derived debris arrived from western Canada into central Alaska and subsequently moved to the north (arctic) and to the west, decreasing in the quantity deposited as the debris transversed the state.

Key words: Chernobyl, radiocesium, lichen, mushroom, caribou, reindeer, soil, fallout, deposition

RÉSUMÉ. On a mesuré les concentrations de césium radioactif (^{134}Cs et ^{137}Cs) dans des échantillons de sol, de plantes et d'animaux, dans la région allant de l'Alaska subarctique à l'Alaska arctique. Les concentrations de ^{137}Cs allaient de niveaux peu élevés ou inférieurs au point de détection dans des échantillons de baleine et de poisson, à des niveaux qui atteignaient 242 Bq/kg dans le lichen. Pour toutes les formes potentielles d'alimentation humaine, les concentrations de césium radioactif mesurées au cours de l'étude étaient inférieures au niveau reconnu acceptable pour la consommation humaine. Les concentrations de césium radioactif provenant de Chernobyl allaient de niveaux peu élevés ou inférieurs au point de détection dans tous les échantillons provenant de l'Arctique (sol, sédiments, lichen, baleine, poisson et caribou), à 32 Bq/kg dans la mousse subarctique. La répartition et le dépôt subséquent du césium radioactif provenant de Chernobyl semblent donc varier, selon un mode nettement décroissant du Subarctique (Fairbanks) à l'Arctique. Les données actuelles viennent appuyer l'hypothèse que les débris provenant de Chernobyl sont arrivés de l'ouest du Canada dans le centre de l'Alaska et se sont ensuite déplacés vers le nord (Arctique) et vers l'ouest, se déposant en quantité décroissante au fur et à mesure qu'ils traversaient l'État.

Mots clés: Chernobyl, césium radioactif, lichen, champignon, caribou, renne, sol, retombées, dépôt

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INTRODUCTION

It has been estimated that for all fallout radionuclides from atmospheric weapons testing, radiocesium alone (primarily ^{137}Cs) contributes about 50% of the total radiation dose to humans in the Northern Hemisphere (Goldman, 1987). Recognizing the importance of radiocesium in radiation dosimetry, investigators have focused considerable attention on fallout radiocesium and its movement in the subarctic and arctic food chain, especially the fallout to lichen to caribou/reindeer to human/wolf food chain (Baarli *et al.*, 1961; Palmer *et al.*, 1963; Liden and Gustafson, 1967; Miettinen and Hasanen, 1967; Hanson, 1967, 1982; Holleman *et al.*, 1971; Holleman and Stephenson, 1981; White *et al.*, 1986; Skogland, 1987).

There has been a gradual decrease in bioavailable radiocesium since the cessation of atmospheric weapons testing; thus for Alaska, radiocesium concentrations in lichen, caribou and reindeer have decreased from peak concentrations of 1200-1800 Bq/kg in the mid-1960s to less than 300 Bq/kg in January 1986 (White *et al.*, 1986). The total amount of radiocesium discharged into the atmosphere following the Chernobyl accident on 26 April 1986 was at most 5-10% of the total amount of radiocesium released from all atmospheric nuclear weapons tests (Goldman, 1987). However, the Chernobyl radiocesium radiation dose to humans in the Northern Hemisphere has been estimated to be about 60% of the total radiocesium radiation dose from the earlier atmospheric weapons tests (Goldman, 1987). This unusually high radiation dose from a significantly smaller quantity of atmospheric released radiocesium is primarily due to the relatively close proximity of large human populations near the Chernobyl accident site, namely, in the central U.S.S.R. and eastern Europe.

Chernobyl-derived radiocesium can be identified by the presence of ^{134}Cs and provides a unique means to assess the pattern of environmental distribution, deposition and subsequent movement of fallout radionuclides from a single event occurring in the Northern Hemisphere. Knowledge of such patterns for atmospheric released radionuclides from the Chernobyl accident may be helpful in evaluating the potential effects of future accidents as well as in understanding the transport pathways and processes of radionuclides associated with such accidents in the atmospheric, terrestrial and aquatic reservoirs (Santschi *et al.*, 1988). Highly variable regional deposition rates of Chernobyl-derived radionuclides have been reported from Scandinavia, Germany, the United Kingdom and the Mediterranean region, as suggested by the wide-ranging values, for example, from 40 to several thousand Bq/m^2 (Davidson *et al.*, 1987; Santschi *et al.*, 1988). In the western United States, the total deposition rate of ^{134}Cs was typically 37-74 Bq/m^2, while at several locations in the Midwest and on the east coast, the values ranged from 3.7 to 37 Bq/m^2 (Davidson *et al.*, 1987). In Alaska, the radiocesium deposition rate was estimated at approximately 0.5 Bq/m^2 for the period April 1986 (pre-Chernobyl) to August 1986 (post-Chernobyl) for the Fairbanks area (White *et al.*, 1986). There is some indirect evidence suggesting wide regional differences in the deposition rate of the Chernobyl-derived radionuclides in Alaska. For example, some airborne measurements show that the integrated radioiodine (^{131}I) concentrations are significantly different in Fairbanks and Barrow (unpubl. data, Kipphut, 1986), which could lead to differences in the deposition rates.

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The objective of the present investigation was to determine radiocesium concentrations in selected environmental samples in subarctic and arctic Alaska. In addition, ^{134}Cs was used to determine the variability and extent of Chernobyl-derived radiocesium in the environment.

MATERIALS AND METHODS

The locations and brief descriptions of the samples used in this study are given in Figure 1 and Table 1. Samples of soil, mixed lichens (primarily *Cladonia* spp.), mushrooms (mixed unidentified spp.), mosses (*Sphagnum* spp.), ledum (*Ledum* spp.), bowhead whale (*Balaena mysticetus*), two anadromous fishes (humpback white fish, *Coregonus clupeaformus*; arctic least cisco, *Coregonus sardinella*) and caribou (*Rangifer tarandus*) were obtained from arctic Alaska. Additional samples of lichens and mushrooms were collected from Ester Dome near Fairbanks. A single lichen sample was collected in extreme western Alaska near Nome. Samples of about 30-60 g of dried soil, 2-11 g of dried lichen/moss/ledum and 60 g of wet (frozen until ground) whale/fish/caribou muscle were ground using a blender. The ground samples were transferred into aluminum cans, capped and then analyzed using a Princeton Gamma (GeLi) detector coupled to a 4096 Channel Multichannel Analyzer (Canberra Industries, Inc.). The detector was shielded by approximately 10 cm of lead and there were no ^{134}Cs or ^{137}Cs peaks in the background spectrum.

TABLE 1. Collection site, date and description of samples

Sample code	Material	Collection date	Collection site
Arctic samples			
A1	soil, lichen	1987	Unknown site on arctic coast
A2	soil, lichen	1987	Atkasuk (70.0°N, 156.3°W)
A3	lichen	1987	Unknown site on arctic coast
A4	soil, lichen	1987	Anaktuvuk Pass (68.1°N, 151.7°W)
A5	lichen	1987	Anaktuvuk Pass
A6	soil, lichen	1987	Unknown site on arctic coast
A7	soil, lichen	1987	Research site (68.5°N, 149.3°W)
A8	lake sediment	1987	Barrow Lake (71.2°N, 156.7°W)
A9	white fish	1987	Colville River (70.0°N, 151.0°W)
A10	least Cisco	1987	Colville River
A11	bowhead whale	1987	Arctic Ocean (71.0°N, 157.0°W)
A12	bowhead whale	1987	Arctic Ocean
A13	caribou	Oct. 1985	Barrow (71.2°N, 156.7°W)
A14	caribou	Nov. 1986	Barrow
A15	caribou	Sept. 1987	Colville River
Subarctic samples			
S1-S2	lichen	July 1988	Fairbanks (64.8°N, 147.7°W)
S3	moss	July 1988	Fairbanks
S4	ledum	July 1988	Fairbanks
S5-S9	mushrooms	Aug. 1988	Fairbanks
S10	lichen	1987	Nome (64.5°N, 165.2°W)

Counting times ranged from 12 to 48 h. The minimum detection limits were 0.21 and 0.28 Bq/kg for ^{134}Cs and ^{137}Cs respectively, based on a 48 h count and the 95% confidence level. The details on the counting procedure and data analysis are given in Baskaran *et al.* (1988).

For those samples in which ^{134}Cs was detected, the quantity of ^{137}Cs that was derived from the Chernobyl accident was calculated. The procedure and its assumptions are as follows. Due to its relatively short physical half-life (2.05 yr), all ^{134}Cs was assumed to be Chernobyl-derived. The $^{137}Cs/^{134}Cs$ ratio for Chernobyl released radiocesium at the time of the accident, 26 April 1986, was taken to be equal to 2.5 (Watson, 1986; Davidson *et al.*, 1987). A decay corrected ratio was calculated by correcting for physical decay of both isotopes from the time of accident to the time of sample assay. The Chernobyl-derived ^{137}Cs concentration of the sample was calculated as the product of the measured ^{134}Cs concentration and the decay corrected ratio. All radiocesium concentrations are reported in Bq/kg as of the time of counting, winter 1988.

RESULTS AND DISCUSSION

The total concentrations of ^{134}Cs and ^{137}Cs in the samples as well as the ^{137}Cs concentrations derived from the Chernobyl accident are given in Table 2. The radiocesium concentrations are presented as radioactivity per unit dry-weight for the soil and plant samples and as radioactivity per unit wet-weight for the fish, whale and caribou samples. The errors in the activity are propagated 1 sigma error arising from counting statistics, background and efficiency of the detector.

^{137}Cs Concentration in Soils and Lichens

^{137}Cs levels in the arctic soil samples analyzed are generally lower than in the arctic lichens and the ^{134}Cs levels are below detection limit in all the soil samples (Table 2). The ^{137}Cs concentrations ranged from 2.1 to 44.0 Bq/kg, with a geometric mean of 7.3 Bq/kg, in the soil samples and from 16.3 to 24.2 Bq/kg, with a geometric mean of 59.9 Bq/kg, in lichen samples. This range of ^{137}Cs concentration is comparable to the range of 59-181 Bq/kg reported earlier for lichens in the study area just before the Chernobyl accident (Hanson, 1982; White *et al.*, 1986). However, the mean concentration (59.9 Bq/kg) of our arctic lichen samples is much lower than the values (approximately 600 Bq/kg) expected from the physical decay of ^{137}Cs for the values reported between 1962 and 1968 (925-1100 Bq/kg). The ratio of ^{137}Cs concentration in lichens to soils varies from 0.51 to 28.2 (ratio of geometric mean = 59.9/7.3 = 8.2). Earlier studies have shown that the ^{137}Cs concentrations in lichens were about five times those in soil (Hanson, 1982). The ratios of less than 1.0 could be due to new lichen growth that has been exposed to low levels of fallout ^{137}Cs.

^{137}Cs Concentrations in Fish and Whale Tissues

Of the two fish analyzed, the freshwater species (humpback whitefish) had ^{137}Cs concentration below the detection limit, while that of the estuarine fish (least cisco whitefish) had a low concentration (0.52+0.09 Bq/kg). The ^{137}Cs concentration was below the detection limit in bowhead whale blubber and liver, while the muscle sample had a low concentration of ^{137}Cs (0.57 Bq/kg). This may be expected since fallout radio-

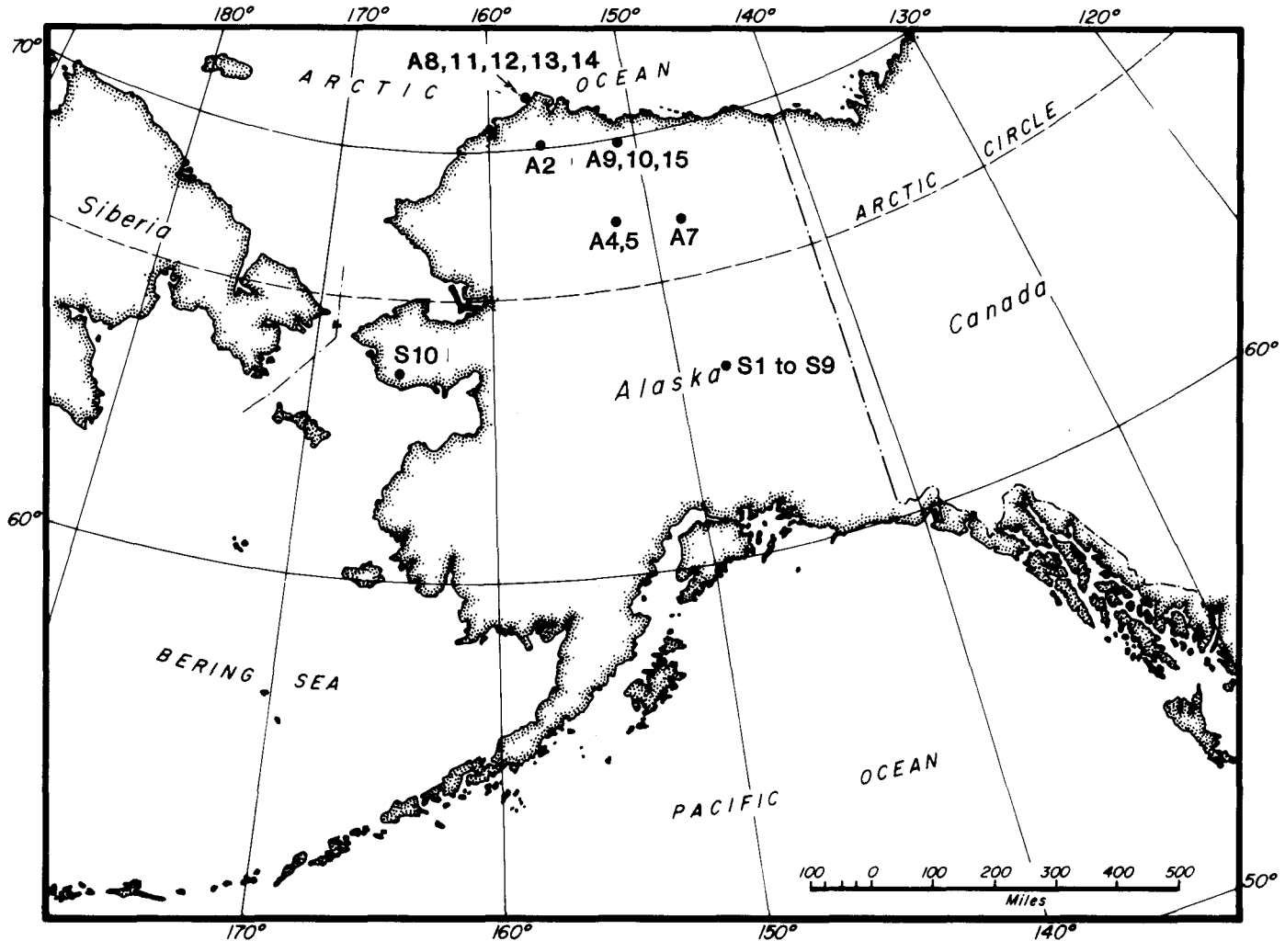

FIG. 1. Locations of the samples analyzed. Refer to Table 1 for further details.

cesium is greatly diluted in seawater and, as a result, the bowhead whale's prey is unlikely to concentrate ^{137}Cs, despite high fallout.

^{134}Cs and ^{137}Cs Concentration in Caribou

The seasonal variation in radiocesium concentrations in caribou muscle samples has been recognized for a long time (Hanson, 1982) and appears to follow the change in the pattern of grazing habits; for example, low values of ^{137}Cs are generally found in caribou muscle tissues following the summer feeding season, when the caribou's diet is mostly vascular plants and sedges. These summer forages contain much lower ^{137}Cs concentrations than do lichens, a forage consumed extensively during winter. Another possible factor of significance for the low ^{137}Cs levels in caribou during summer is the relatively higher excretion of ^{137}Cs during summer as compared to winter (Holleman *et al.*, 1971). It has been shown that the model-derived value of three- to sevenfold increase in radiocesium levels needed to explain the seasonal variation in radiocesium concentration (Holleman *et al.*, 1971) agrees reasonably well with empirical data obtained by Hanson (1982), reporting a five- to tenfold seasonal difference. The muscle sample of caribou harvested in September 1987 has perhaps the lowest ^{137}Cs concentrations reported after the last series of nuclear tests (Table 2).

Permissible Concentrations for Human Consumption

The maximum permissible intake for ^{137}Cs is approximately 100 000 Bq/yr for a human adult. This value is calculated from the radiation dose limit for the whole population of 1.7 mSv/yr (NCRP, 1971) and the radiation dose equivalent of 0.000017 mSv per Bq of ^{137}Cs intake (NCRP, 1977). Such limits suggest permissible concentrations in human food items ranging from 300 Bq/kg for milk and meat to 1500 Bq/kg for berries and mushrooms. Similar values for permissible concentrations of ^{137}Cs in human foods were adopted by the Scandinavian and European countries following the Chernobyl accident (Jones, 1989). The ^{137}Cs concentrations reported here are substantially less than the acceptable limits, thus suggesting little health risk for persons consuming foods at these ^{137}Cs concentrations. A similar conclusion was reported by Taylor *et al.* (1988), who assessed the post-Chernobyl radiocesium levels at some localities in northern Canada.

Deposition of Chernobyl-Derived Radiocesium in Alaska

The Chernobyl-derived ^{134}Cs in all samples collected in the Arctic, namely, above 67°N, were below the detection limit with the exception of a single caribou sample. The ^{134}Cs concentration for the caribou sample was 0.4 Bq/kg, which was only slightly above the detection limit. Perhaps this could be attributed to the fact that snow cover existed on the arctic soil when the Chernobyl plume arrived at the study area and that most of the snow-deposited radiocesium was washed away when the snow melted. In this case, we would expect to find high concentrations of radiocesium in lakes in the area. The residence time of radiocesium in lake water was reported to be relatively short. For example, Santschi *et al.* (1988) showed that about 75% of the total fallout of ^{134}Cs and ^{137}Cs in Lake Zurich was eliminated from the water column in about six months. Thus, the washed-out radiocesium should reach the bottom of the lake. In order to see if the ^{134}Cs level was high in a bottom sediment sample, one grab sediment sample was collected from a small pond (71.3°N, 156.2°W) in 1988 and no detectable ^{134}Cs was found in the sample. Also a single sample of lichen (S10) from the extreme west coast of Alaska had no significant ^{134}Cs. The ^{134}Cs concentrations in samples from the subarctic Fairbanks area ranged from below detection to 6.0 Bq/kg. Since lichens were the only environmental samples collected in both the Subarctic and Arctic, these samples were used to assess possible differences in deposition of Chernobyl-derived radiocesium. Concentrations of ^{134}Cs ranged from below detection (0.21 Bq/kg) in all arctic lichen samples to 6.0 Bq/kg in a subarctic lichen sample. Assuming that the physical and physiological aspects of lichens are similar at the various collection sites, e.g., lichen density, radiocesium collection efficiency, etc., then the data in this study suggest the deposition rates were highly variable and were greater than a factor of 28.

TABLE 2. Radiocesium concentrations in selected environmental samples

Sample code	Total activity ^{137}Cs (Bq/kg)	Total activity ^{134}Cs (Bq/kg)	Total activity $^{137}Cs/^{134}Cs$ ratio	Chernobyl-derived ^{137}Cs (Bq/kg)	Chernobyl-derived ^{137}Cs (%)
Arctic soil sediment					
A1	4.1±4.2	BD	—	—	—
A2	44.0±1.3	BD	—	—	—
A4	2.8±3.5	BD	—	—	—
A6	8.1±1.7	BD	—	—	—
A7	2.1±2.2	BD	—	—	—
A8	2.4±2.3	BD	—	—	—
Arctic lichen, moss, ledum					
A1	16.6±4.2	BD	—	—	—
A2	22.3±1.3	BD	—	—	—
A3	92.2±3.5	BD	—	—	—
A4	39.3±1.7	BD	—	—	—
A5	242.0±2.2	BD	—	—	—
A6	39.7±2.3	BD	—	—	—
A7	58.5±4.2	BD	—	—	—
Arctic fish, whale, caribou					
A9	BD	BD	—	—	—
A10	0.52±0.09	BD	—	—	—
A11					
blubber	BD	BD	—	—	—
muscle	0.57±0.11	BD	—	—	—
liver	BD	BD	—	—	—
A12					
blubber	BD	BD	—	—	—
liver	BD	BD	—	—	—
muktuk	BD	BD	—	—	—
A13	60.0±4.2	BD	—	—	—
A14	31.0±1.0	0.4±0.2	77.0	2.1	6.8
A15	1.1±0.2	BD	—	—	—
Subarctic lichen, moss, ledum, mushrooms					
S1	97.0±1.0	5.0±0.4	19.0	27.0	27.7
S2	89.0±1.0	4.6±0.4	19.0	24.0	27.4
S3	86.0±3.0	6.0±2.0	14.0	32.0	37.2
S4	60.0±1.0	4.3±0.4	14.0	23.0	38.2
S5	3.5±1.1	BD	—	—	—
S6	BD	BD	—	—	—
S7	3.8±1.0	BD	—	—	—
S8	32.0±1.0	1.4±0.3	23.0	8.0	24.2
S9	43.0±1.0	5.2±0.3	8.3	28.0	65.4
S10	51.3±2.2	BD	—	—	—

Bq/kg = Becquerel per kilogram.
BD = Below detection.

The present data indicate a low Chernobyl-derived radiocesium deposition in arctic Alaska and on the extreme west coast of Alaska as compared to the subarctic Fairbanks site. It is pertinent to compare this observation with the radioiodine data in the aerosols at Barrow and Fairbanks. The ratio of the time-integrated concentrations of radioiodine at Barrow to that of Fairbanks was 0.628 just after the Chernobyl accident (5-19 May 1986, unpub. data, Kipphut, 1986). These data are consistent with the observations of others who have investigated distribution of Chernobyl debris in North America. For example, Davidson *et al.* (1987) determined that Chernobyl-derived radiocesium moved from the U.S.S.R. and Scandinavia over Greenland and into central Canada then spread to the east and west. Assuming that the debris entered Alaska from the east via Canada, deposition should decrease from eastern to western Alaska. Further, if the Chernobyl debris entered Alaska south of the Brooks Mountain Range, deposition may be expected to decrease significantly going from central to northern Alaska.

CONCLUSIONS

The radiocesium concentrations in all the samples were low and, therefore, present no appreciable health hazard to humans who might consume them directly or indirectly via food chains. The deposition rate of radiocesium from the Chernobyl-derived radiocesium in arctic/subarctic Alaska appears to be highly variable, possibly by a factor of greater than 28. Deposition of radiocesium was greater in subarctic Fairbanks as compared to extreme western and arctic Alaska, which presumably reflects the dispersal pathway of the Chernobyl debris in the area of study.

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