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Results of the Radiological Survey at Two Mile Creek, Tonawanda, New York (TNY002)

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MANAGED AND OPERATED BY
LOCKHEED MARTIN ENERGY RESEARCH CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL-27 (3-96)

ORNL/RASA-96/9

LIFE SCIENCES DIVISION
Environmental Restoration and Waste Management Non-Defense Programs
(Activity No. EX 20 20 01 0; ADS1310AEX)

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Date Issued—August 1997

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for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-96OR22464

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ACKNOWLEDGMENTS

This project was sponsored by the Office of Environmental Restoration, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc., and DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp. The authors wish to acknowledge the contributions of J. F. Allred, W. D. Cottrell, V. P. Patania, D. A. Roberts, and D. A. Rose of the Measurement Applications and Development Group, Oak Ridge National Laboratory, for sample preparation and participation in the analyses, editing, and reporting of data for this survey. The authors also wish to thank the Town of Tonawanda Department of Parks and Recreation and the Society for the Prevention of Cruelty to Animals for their assistance and for the loan of equipment.

ABSTRACT

At the request of the U.S. Department of Energy (DOE), a team from Oak Ridge National Laboratory conducted a radiological survey at Two Mile Creek, Tonawanda, New York. The survey was performed in November 1991 and May 1996. The purpose of the survey was to determine if radioactive materials from work performed under government contract at the Linde Air Products Division of Union Carbide Corporation, Tonawanda, New York, had been transported into the creek. The survey included a surface gamma scan in accessible areas near the creek and the collection of soil, sediment, and core samples for radionuclide analyses.

Survey results indicate that no significant material originating at the Linde plant is presently in the creek. Three of the 1991 soil sample locations on the creek bank and one near the lake contained slightly elevated concentrations of ^{238}U with radionuclide distributions similar to that found in materials resulting from former processing activities at the Linde site. The highest ^{238}U concentration was found in a 2-in. band of soil along the creek bank approximately 3 ft below the current floodplain. Because one sample contained 37 pCi/g ^{238}U, which is slightly above the DOE ^{238}U guideline of 30 pCi/g for the Tonawanda site, additional sampling was conducted in 1996. The 1996 sample results confirmed that a layer of material containing slightly elevated concentrations of ^{238}U has been deposited below the surface of the west bank of Two Mile Creek in a localized area near sample location B3. This layer might possibly be associated with the operation of the Linde plant. However, ^{238}U levels in this subsurface layer are relatively low with all 1996 samples containing concentrations well below the DOE guideline of 30 pCi/g. It was concluded that the 1991 sample containing 37 pCi/g ^{238}U was taken from a small elevated area <25 m^2, which when averaged with other area samples is well below the average and the "hot spot" guideline values.

Results of the Radiological Survey at Two Mile Creek, Tonawanda, New York (TNY002)*

INTRODUCTION

From 1942 through approximately 1948, the Linde Air Products Division of Union Carbide Corporation, Tonawanda, New York, was one of many companies performing work associated with the development of nuclear energy for defense-related projects. This work was conducted under government contract to the Manhattan Engineer District (MED) and the Atomic Energy Commission (AEC). During the first 3 years, pitchblende ore from the Belgian Congo and concentrates from the Colorado Plateau ore were converted to U_3O_8. A second process yielding UO_2 was conducted for about a year, and a third process, converting UO_2 to green salt (UF_4), operated during World War II and the following 2 years. Linde also developed and produced barrier material for the Oak Ridge Gaseous Diffusion Plant. Other contracts have been identified, but the exact nature of the work involved is unknown.[1]

As a result of these and similar activities, equipment, buildings, and land at some of the sites became radiologically contaminated resulting in low levels of contamination on the properties. At contract termination, sites used by contractors were decontaminated in accordance with the standards and survey methods in use at that time. Since the original assessments, radiological criteria and guidelines for the release of such sites for unrestricted use have become more stringent. In some instances, records documenting decontamination efforts cannot be found, and the final radiological conditions of the site cannot be adequately determined. As a result, the Formerly Utilized Sites Remedial Action Program (FUSRAP) was established in 1974 to identify these formerly used sites and to reevaluate their radiological status.[1] The radiological survey detailed in this report was performed under the FUSRAP program.

The Linde site has been previously investigated to determine the extent of on-site radiological contamination. As a follow-up to earlier investigations and as a precaution to ensure that no residual radioactive materials exceeding current U.S. Department of Energy (DOE) guidelines were transported off-site, DOE requested a radiological survey in the vicinity of the Linde site. The 1990 report on this effort[2] recommended a complete survey of Two Mile Creek from south of the Linde property to its confluence with the Niagara River. This recommendation was made because Two Mile Creek received drainage from the Linde Plant sewers during the 1940–1948 contract operations and because previous samples of plant outfall and downstream water from Two Mile Creek taken in 1976 showed concentrations of radium and uranium 3 to 5 times those of upstream samples.[3]

In November 1991, a radiological survey was conducted at Two Mile Creek by personnel from Oak Ridge National Laboratory at the request of DOE. After analysis of results of the 1991 survey, additional samples were collected at the site in May 1996. This report presents results of both the 1991 and the 1996 site investigations. The general location of Two Mile Creek in relation to the Linde site is shown in Fig. 1.

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*The survey was performed by members of the Measurement Applications and Development Group of the Life Sciences Division at Oak Ridge National Laboratory under DOE contracts DE-AC05-84OR21400 and DE-AC05-96OR22464.

The creek, a low-flow tributary of the Niagara River that flows from south to north, was surveyed from the point it emerges from underground, near the Linde site in the Town of Tonawanda, to the point it discharges into the Niagara River in the City of Tonawanda (see Fig. 2). The portion of the creek that originally paralleled the Linde site has, in recent years, been directed underground and could not be accessed by the survey team. At the northwestern end of the Linde site, the creek emerges from underground and forms a small lake prior to passing under Sheridan Drive. North of Sheridan Drive, a dam on the creek produces a larger lake (~200 ft across at the widest point). North of the lake, the width of the creek varies from 7 to 30 ft. At the time of the survey, the stream flow was low, and, in most places, the stream was less than 18 in. deep. However, the creek does have periods of great flow because it is the primary transporter of storm runoff. High water marks and miscellaneous debris several feet above the typical water level indicated periods of extreme flooding.

SCOPE OF THE SURVEY

The original radiological survey in 1991 included: (1) a surface gamma scan of accessible areas along the bank and streambed; (2) collection and radionuclide analysis of 36 biased soil samples collected at 12 locations shown to have elevated gamma exposure rates; (3) collection and radionuclide analysis of 18 sediment samples from Two Mile Creek; and (4) collection and radionuclide analysis of 36 core samples collected at 12 locations in Two Mile Creek. The 1996 survey included the collection and analysis of 63 additional biased soil samples at 13 locations in a particular section of the creek bank.

SURVEY METHODS

A comprehensive description of the survey methods and instrumentation used in this survey is given in *Procedures Manual for the ORNL Radiological Survey Activities (RASA) Program*, ORNL/TM-8600 (April 1987)[4] and *Measurement Applications and Development Group Guidelines*, ORNL-6782 (January 1995).[5]

GAMMA RADIATION MEASUREMENTS

Gamma radiation levels were determined using portable NaI gamma scintillation meters. Because NaI gamma scintillators are energy dependent, measurements of gamma radiation levels in counts per minute are normalized to pressurized ionization chamber (PIC) measurements to estimate gamma exposure rates in μR/h. The area covered by the gamma scan generally ranged approximately 10 to 30 ft from the water's edge.

SOIL, SEDIMENT, AND CORE SAMPLING AND ANALYSES

Surface and subsurface soil samples were collected at areas along the bank and streambed where elevated gamma exposure rates had been identified during the gamma scan. Additional surface and subsurface soil samples were collected at a localized area on the bank when radiological analysis of an earlier sample indicated possible contamination might exist. Sediment and core samples were strategically taken at locations where side streams (some from the Linde site) enter the main stream and at places where the linear velocity of the stream was low giving possible contaminants an opportunity to settle. Sediment samples containing 4 to 6 in. of sediment were scooped from the middle of Two Mile

Creek. Core samples were collected by driving a section of pipe (2.5 in. diameter) down into the creek bottom as far as possible (to refusal). The pipe was capped and later frozen and cut into sections before analysis. All soil, sediment, and core samples were analyzed by gamma spectrometry.

SURVEY RESULTS

DOE guidelines are summarized in Table 1. Typical background radiation levels for the Tonawanda, New York, area are presented in Table 2. These data are provided for comparison with survey results presented in this section. All direct measurement results presented in this report are gross readings; background radiation levels have not been subtracted. Similarly, background concentrations have not been subtracted from radionuclide concentrations measured in soil, sediment, and core samples.

Photographs of the survey area taken in November 1991 are shown in Figs. 3 through 6.

GAMMA EXPOSURE RATE MEASUREMENTS

Results of the surface gamma scan of accessible areas ~10 to 30 ft from the edge of Two Mile Creek are shown in Fig. 7. Gamma exposure rates along the creek generally ranged from 7 to 11 μR/h. These values are similar to typical background radiation levels in the Tonawanda area (8 to 11 μR/h, Table 2). An area of elevated spots ranging from 13 to 78 μR/h was identified adjacent to Two Mile Creek Road near Fletcher Street. The elevated spots were scattered over a one-quarter-acre area (Fig. 8). Soil samples collected in this area showed that the elevated gamma levels were caused by chunks of rock buried in the soil (Fig. 9).

Slightly elevated gamma exposure rates were noted along the middle region of the west bank of Two Mile Creek. This slight elevation followed the pattern shown in Fig. 10 with gamma exposure rates of 11 μR/h at the bottom and top of the bank and levels rising to 13 μR/h near the middle of the bank. This elevation was evident along the bank extending approximately one-quarter mile on either side of the 11- to 20-μR/h spot noted on Fig. 7 between Fletcher Street and Youngman Memorial Highway.

One spot measuring 13 μR/h was found between Youngman Memorial Highway and Ensminger Road (Fig. 7), and three spots ranging from 9 to 13 μR/h were identified around the lake at the southernmost part of the surveyed area (Fig. 7).

BIASED SOIL SAMPLES—1991

Biased soil sample locations for samples collected in 1991 (B1 through B12) are shown in Figs. 11 and 12. Results of analyses are listed in Table 3. For samples B1 through B12, concentrations of ^{238}U and ^{226}Ra in surface soil (0–15 cm) ranged from 1.2 to 400 pCi/g and from 0.90 to 390 pCi/g, respectively. Concentrations in subsurface soil (15–105 cm, samples B1 through B12) ranged from 1.8 to 37 pCi/g and from 0.92 to 16 pCi/g, respectively. Because slag, cinders, and other similar materials scattered throughout the Tonawanda–Niagara Falls area contain naturally occurring radionuclides that may cause slight elevations in radionuclide concentrations, samples B2, B3A–C, B5A–D, B6A–C, B8, B9A–C, B10A–B, B11A–D, and B12A–C are considered to be within typical background levels for ^{238}U

and ^{226}Ra in the Tonawanda area (Table 2). Naturally occurring uranium contains roughly equal amounts of ^{226}Ra and ^{238}U.

Rock samples B2R and B7R containing 220 and 400 pCi/g of ^{238}U, 190 and 390 pCi/g of ^{226}Ra, and 340 and 290 pCi/g of ^{232}Th, respectively, were collected in the one-quarter-acre area of elevated spots along Two Mile Creek Road near Fletcher Street. The elevated spots were due to chunks of rock scattered throughout this area, primarily in the top 6 in. of soil. The rocks appeared to be of natural origin. Since the the rocks were located 100 to 200 m from the creek and the pattern of radionuclide distribution in the analyzed samples was completely unlike that found in materials originating from the Linde site, the rocks were judged to be unrelated to the survey of Two Mile Creek.

Samples B1, B1B, B3D–G, and B4A–B with elevated concentrations of ^{238}U and, in most cases, lower concentrations of ^{226}Ra were similar to materials that resulted from former processing activities at the Linde site. These samples were collected along the west bank of Two Mile Creek in a pattern shown in Fig. 11. As noted earlier, slightly elevated surface gamma exposure rates were evident along the bank extending approximately one-quarter mile on either side of sample locations B1 and B3–6 (Fig. 13). Sample B1 and B1B containing 18 and 16 pCi/g of ^{238}U were scooped from the bank at the point with the highest surface gamma exposure rate (Fig. 11). Samples B4A and B4B containing 21 and 25 pCi/g ^{238}U were collected 1 ft downstream from sample B1 at depths of 0 to 12 in. (Fig. 11). Samples B3D–G containing 20 to 37 pCi/g of ^{238}U were collected ~3 ft from the edge of the bank (Figs. 11 and 14). These results suggested that a layer of material containing ^{238}U possibly associated with the operation of the Linde plant might be deposited below the surface of the west bank of Two Mile Creek in this region. Results from the 1991 samples indicated that ^{238}U concentrations in this layer were relatively low. All samples except B3F were below current guidelines for ^{238}U and ^{226}Ra applied at the Tonawanda site (Table 1). Sample B3F containing 37 pCi/g of ^{238}U was only slightly above the guideline of 30 pCi/g for ^{238}U. However, the lateral extent of subsurface contamination in this area was not well defined, and additional sampling was planned.

Samples B12D and B12E collected near Two Mile Creek lake also contained slightly elevated concentrations of ^{238}U (9.0 and 15 pCi/g) and much lower concentrations of ^{226}Ra (1.5 and 3.0 pCi/g). This material, which is well below the guideline value for the Tonawanda area (Table 1), might possibly have originated at the Linde site.

Excluding samples B2R and B7R (discussed earlier), ^{232}Th concentrations in all other biased samples ranged from 0.79 to 3.1 pCi/g, which is similar to or only slightly above typical background ^{232}Th levels from the Tonawanda area (Table 2) and well below DOE guideline values for surface and subsurface soil (Table 1).

BIASED SOIL SAMPLES—1996

Biased soil sample locations for samples collected in 1996 are shown in Fig. 15. All were collected in the general location of 1991 samples B1, B3, B4, B5, and B6 (Figs. 11, 12, and 16). Results of analyses are listed in Table 3 (B13 through B25). Concentrations of ^{238}U and ^{226}Ra ranged from 0.75 to 23 pCi/g and from 0.64 to 4.9 pCi/g, respectively. Samples B15D, B16D, B17E, B18D–F, B19D–G, B20D–F, B21D–E, B22E–G, B23D–E, and B25E–F confirmed that a layer of material containing slightly elevated ^{238}U is deposited below the surface of the west bank of Two Mile Creek in this region. This layer might possibly be associated with the operation of the Linde plant. However, ^{238}U levels in

this layer are relatively low with all ^{238}U concentrations well below the guideline of 30 pCi/g for this site (Table 3). Sample locations B13, B14, and B24 appear to be outside the boundary of the slightly elevated subsurface layer.

At some areas in Tonawanda, samples have contained elevated concentrations of ^{230}Th relative to ^{226}Ra. Under normal conditions, these two radionuclides would be present in roughly equal amounts. As an added precaution, two samples were selected for ^{230}Th analysis. Sample B3E (collected in 1991) contained 19 ± 3 pCi/g ^{230}Th and adjacent sample B15D (collected in 1996) contained 3.4 ± 0.6 pCi/g ^{230}Th. Radium-226 in the two samples measured 16 ± 0.2 pCi/g and 2.0 ± 0.2 pCi/g , respectively. Since the concentration of ^{230}Th is roughly equivalent to the concentration of ^{226}Ra, there is no detectable enhancement of ^{230}Th concentrations.

SEDIMENT SAMPLES—1991

Sediment sample locations are shown on Fig. 17, and results of analyses are listed in Table 3. Concentrations of ^{238}U and ^{226}Ra ranged from 0.68 to 6.5 pCi/g and 0.55 to 1.7 pCi/g, respectively. Concentrations of ^{232}Th ranged from 0.34 to 1.0 pCi/g. Although sample E6 shows very slightly elevated concentrations of ^{238}U (6.5 pCi/g), all other samples are near or only slightly above typical background concentrations in soil from the Tonawanda area (Table 2). All samples are well below DOE guideline values (Table 1).

CORE SAMPLES—1991

Core sample locations are shown on Fig. 18, and results of analyses are listed in Table 3. Concentrations of ^{238}U and ^{226}Ra ranged from 0.89 to 5.3 pCi/g and 0.55 to 1.4 pCi/g, respectively. Concentrations of ^{232}Th ranged from 0.42 to 1.2 pCi/g. Although sample A1E shows very slightly elevated concentrations of ^{238}U (5.3 pCi/g), all other samples are near or only slightly above typical background concentrations in soil from the Tonawanda area (Table 2). All samples are well below DOE guideline values (Table 1).

SIGNIFICANCE OF FINDINGS

Results of this radiological survey indicate that no significant material originating at the Linde plant is located in Two Mile Creek, Tonawanda, New York. Naturally occurring uranium contains roughly equal amounts of ^{226}Ra and ^{238}U. When concentrations of ^{238}U and ^{226}Ra were compared in 1991 biased soil samples, samples B1, B1B, B3D–G, B4A–B, and B12D–E contained slightly elevated concentrations of ^{238}U and, in most cases, lower concentrations of ^{226}Ra. The radionuclide distribution in these samples was similar to that found in materials resulting from former processing activities at the Linde site. Because sample B3F contained 37 pCi/g ^{238}U, which is slightly above the DOE guideline of 30 pCi/g ^{238}U for the Tonawanda site, additional sampling was conducted in 1996. The 1996 sample results confirmed that a layer of material containing slightly elevated concentrations of ^{238}U is deposited below the surface of the west bank of Two Mile Creek in an area near sample location B3. This layer might possibly be associated with the operation of the Linde plant. However, ^{238}U levels in this subsurface layer are relatively low with all 1996 samples containing concentrations well below the guideline of 30 pCi/g. It was concluded that the 1991 sample containing 37 pCi/g ^{238}U was taken from a small elevated area <25 m^2, which when averaged with other area samples is well below the average and the "hot spot" guideline values (Table 1).

Sediment sample E6 and core sample A1E also showed very slightly elevated concentrations of ^{238}U (6.5 and 5.3 pCi/g, respectively), but these levels are well below DOE guideline values.

Samples of rock scattered beside Two Mile Creek Road near Fletcher Street contained elevated concentrations of ^{238}U, ^{226}Ra, and ^{232}Th (up to 400, 390, and 340 pCi/g, respectively). The rocks appeared to be of natural origin. The pattern of radionuclide distribution in these samples is unlike that found in materials originating from the Linde site.

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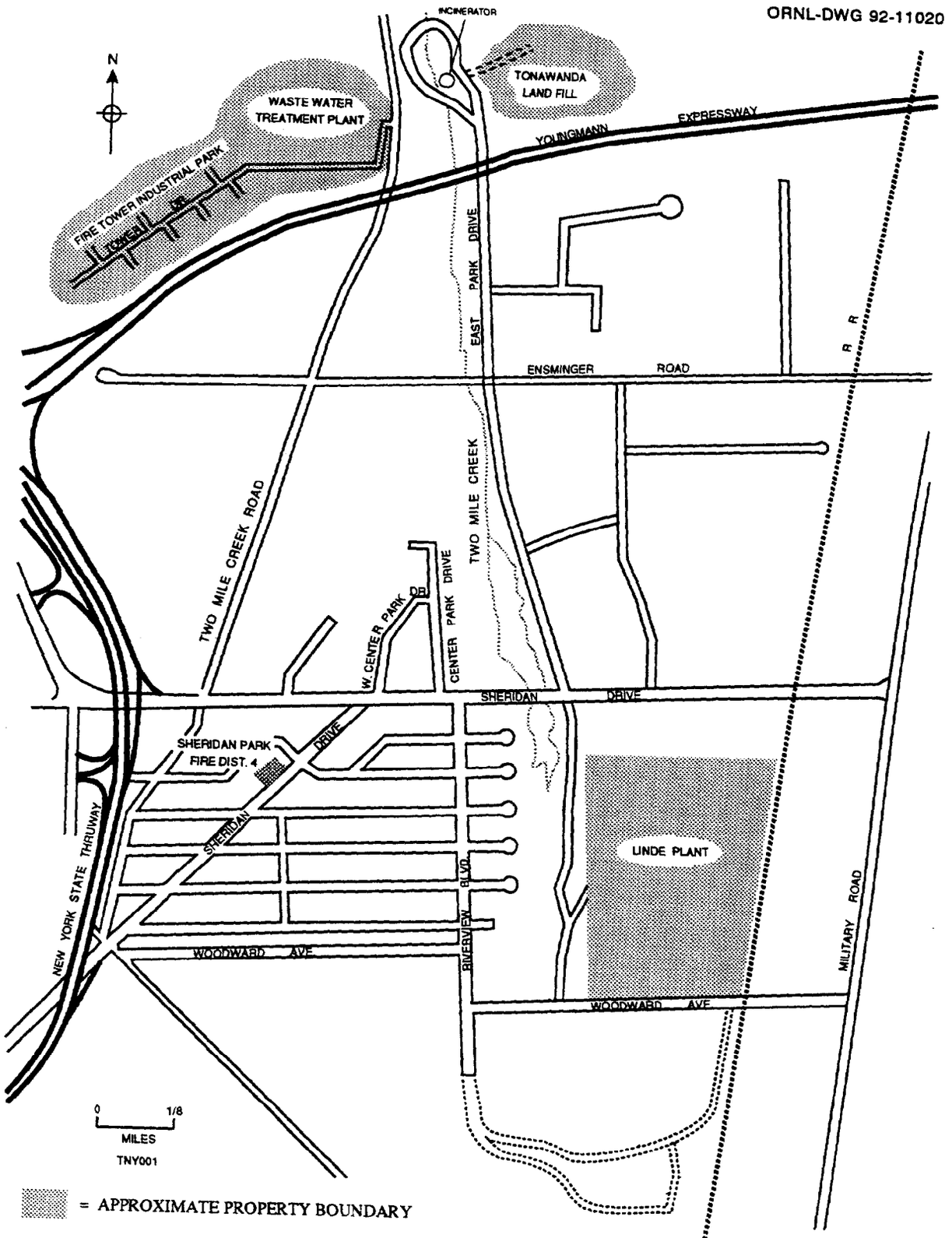

Fig. 1. Diagram showing general location of Two Mile Creek in relation to the Linde site in Tonawanda, New York.

ORNL-DWG 92-12853

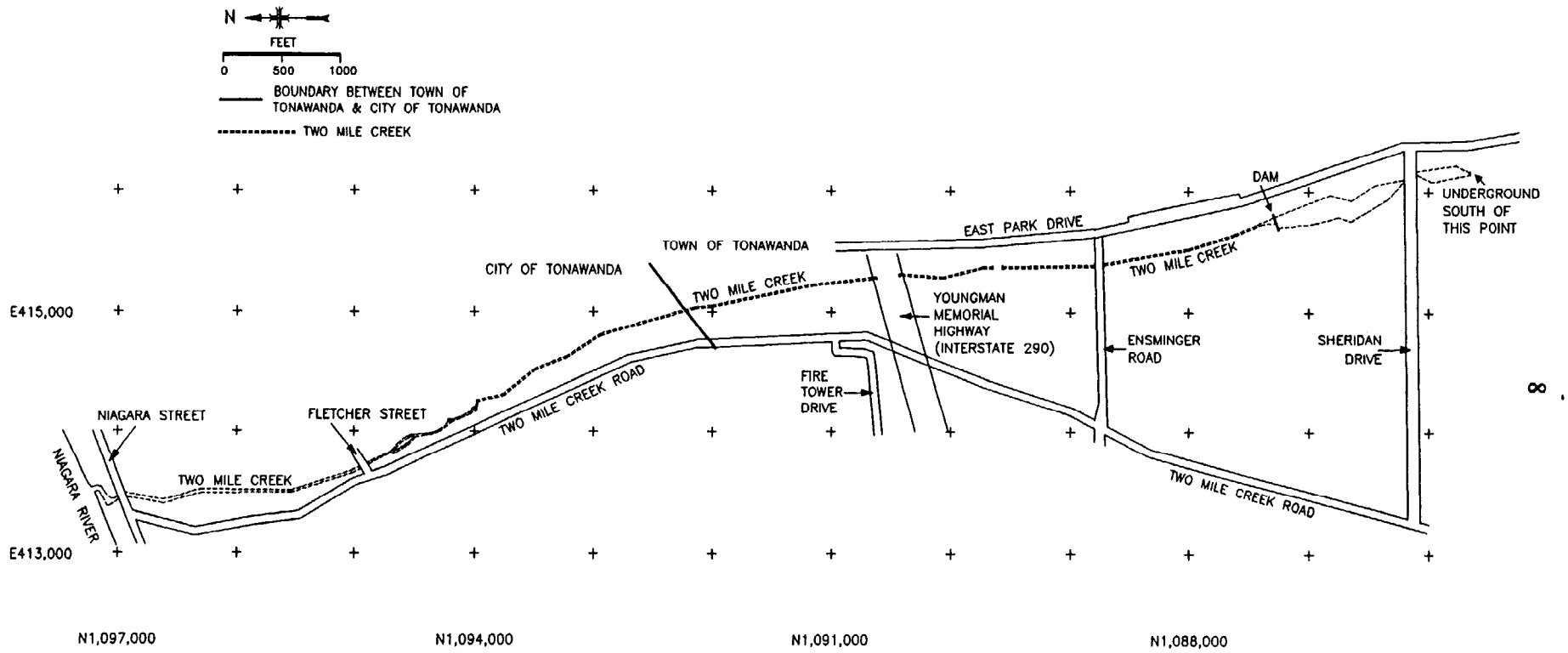

Fig. 2. Diagram showing portion of Two Mile Creek included in the survey.

ORNL-PHOTO 10228-92

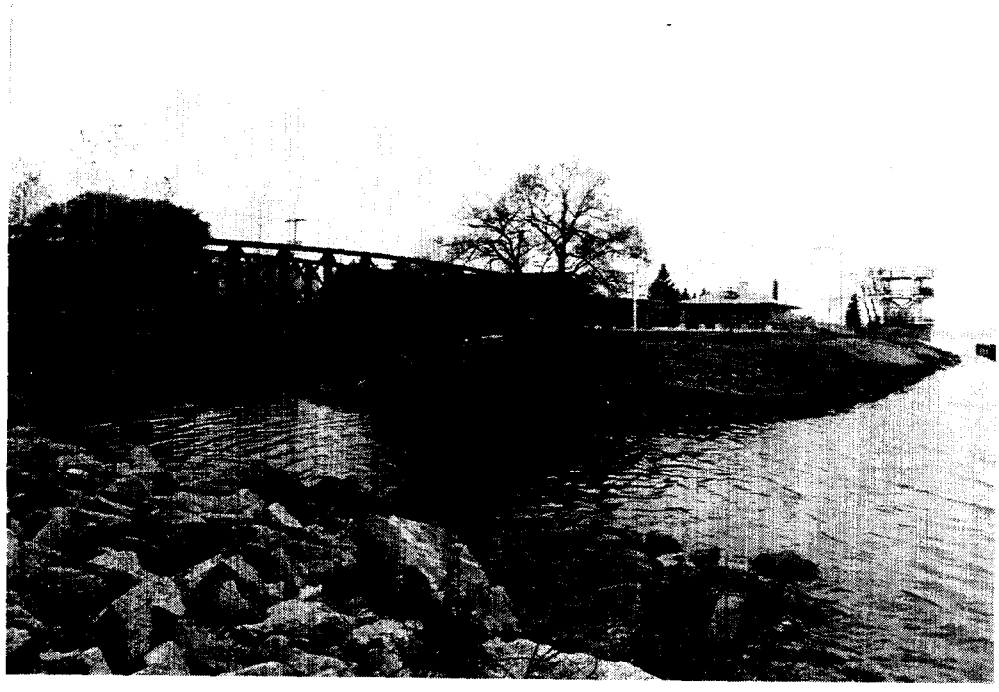

Fig. 3. Two Mile Creek as it enters the Niagara River (extreme right of photo) in the City of Tonawanda, New York.

ORNL-PHOTO 10229-92

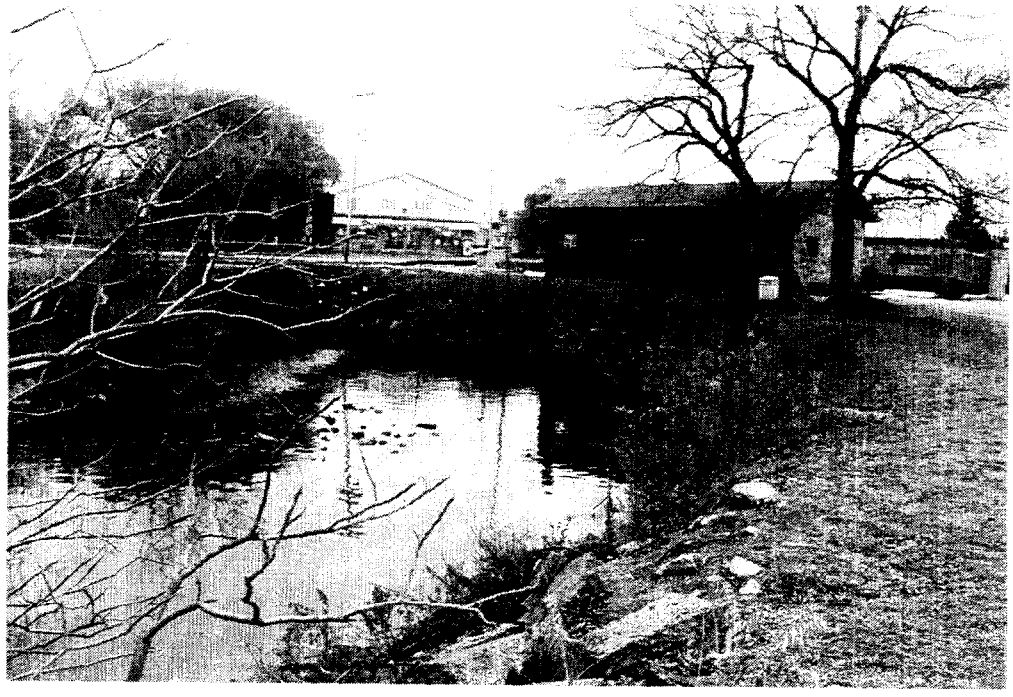

Fig. 4. View looking south at area of sample location A1.

ORNL-PHOTO 10230-92

Fig. 5. Core sampling at edge of Two Mile Creek near Sheridan Drive.

ORNL-PHOTO 10231-92

Fig. 6. Two Mile Creek lake at the southern end of the survey area. The dam is shown in the background.

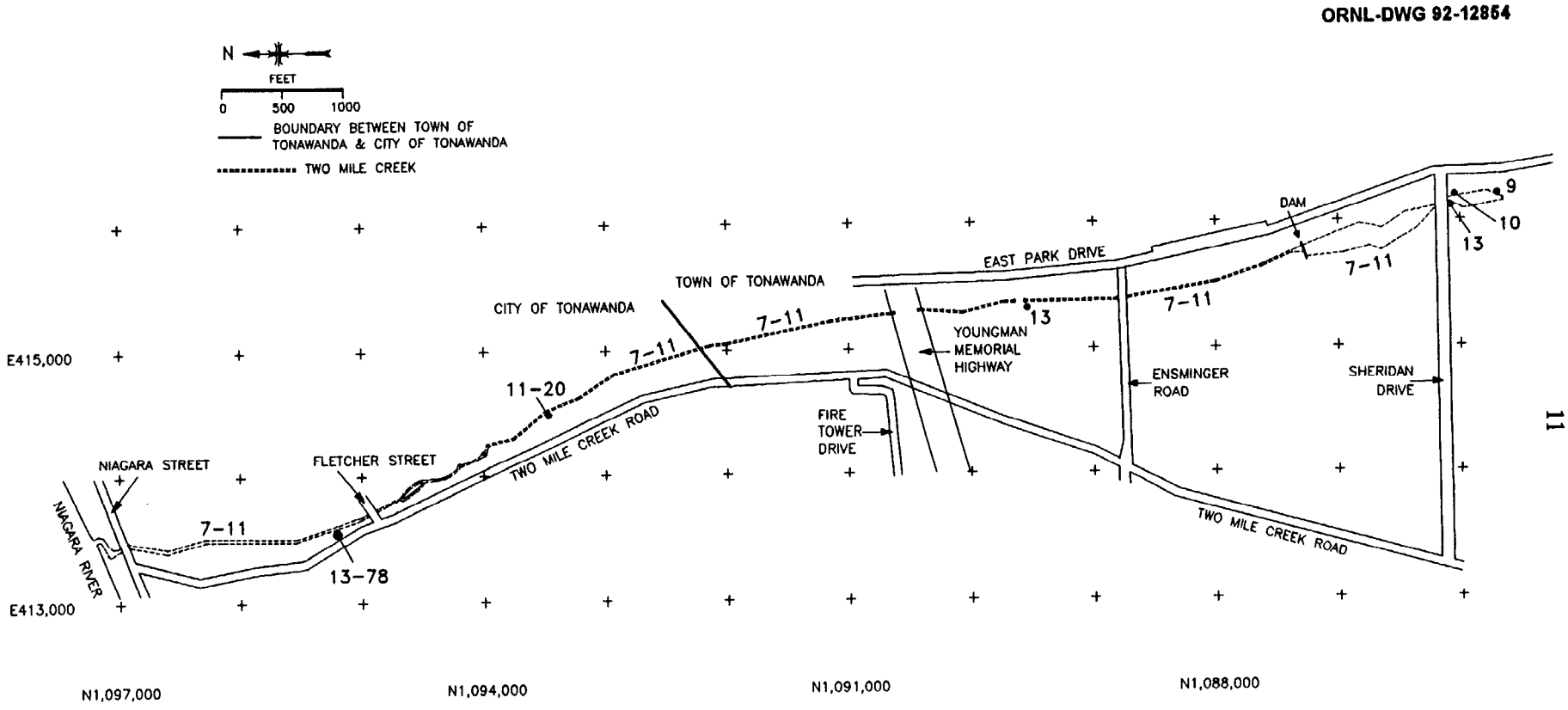

Fig. 7. Diagram showing surface gamma exposure rates (μR/h) in accessible areas ranging approximately 10 to 30 ft from the edge of Two Mile Creek.

ORNL-PHOTO 10232-92

Fig. 8. View of flags marking elevated spots in area along Two Mile Creek Road near Fletcher Street. Samples B2, B7, and B8 were collected in this area.

ORNL-PHOTO 10233-92

Fig. 9. Sample location B2 near Two Mile Creek Road. Scattered chunks of rock were responsible for the elevated surface gamma exposure rates in this area.

ORNL-DWG 92-12855

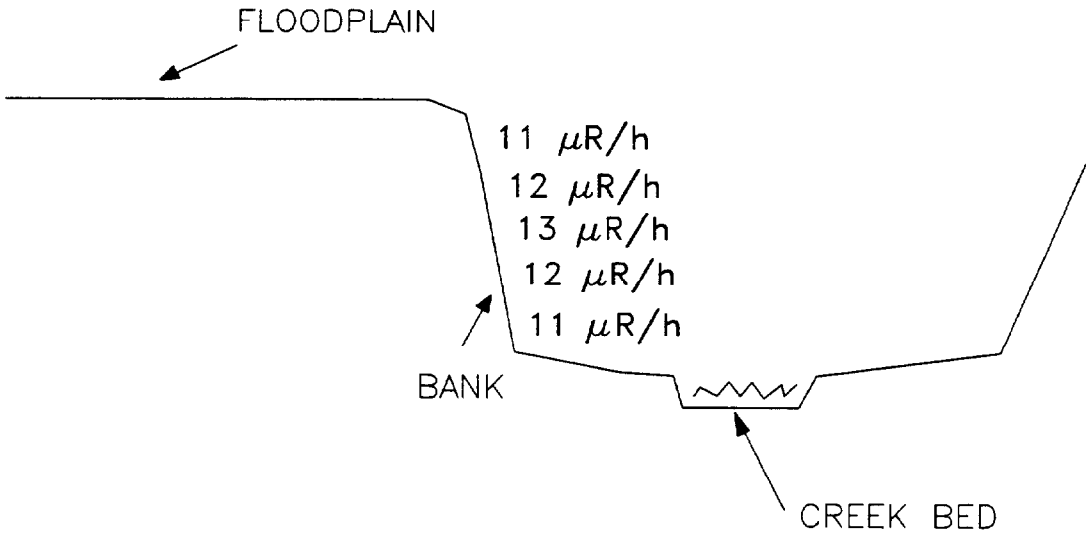

Fig. 10. Cross section of Two Mile Creek showing surface gamma exposure rates (μR/h) on the creek bank at elevated area between Fletcher Street and Youngman Memorial Highway. Diagram not drawn to scale.

ORNL-DWG 92-12856

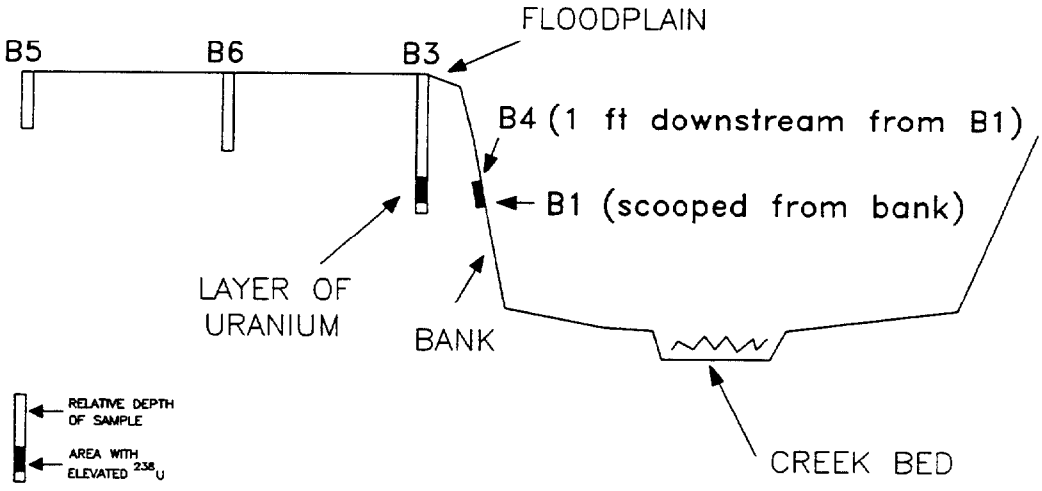

Fig. 11. Cross section of Two Mile Creek showing 1991 biased soil sampling locations at the elevated area between Fletcher Street and Youngman Memorial Highway. Diagram not drawn to scale.

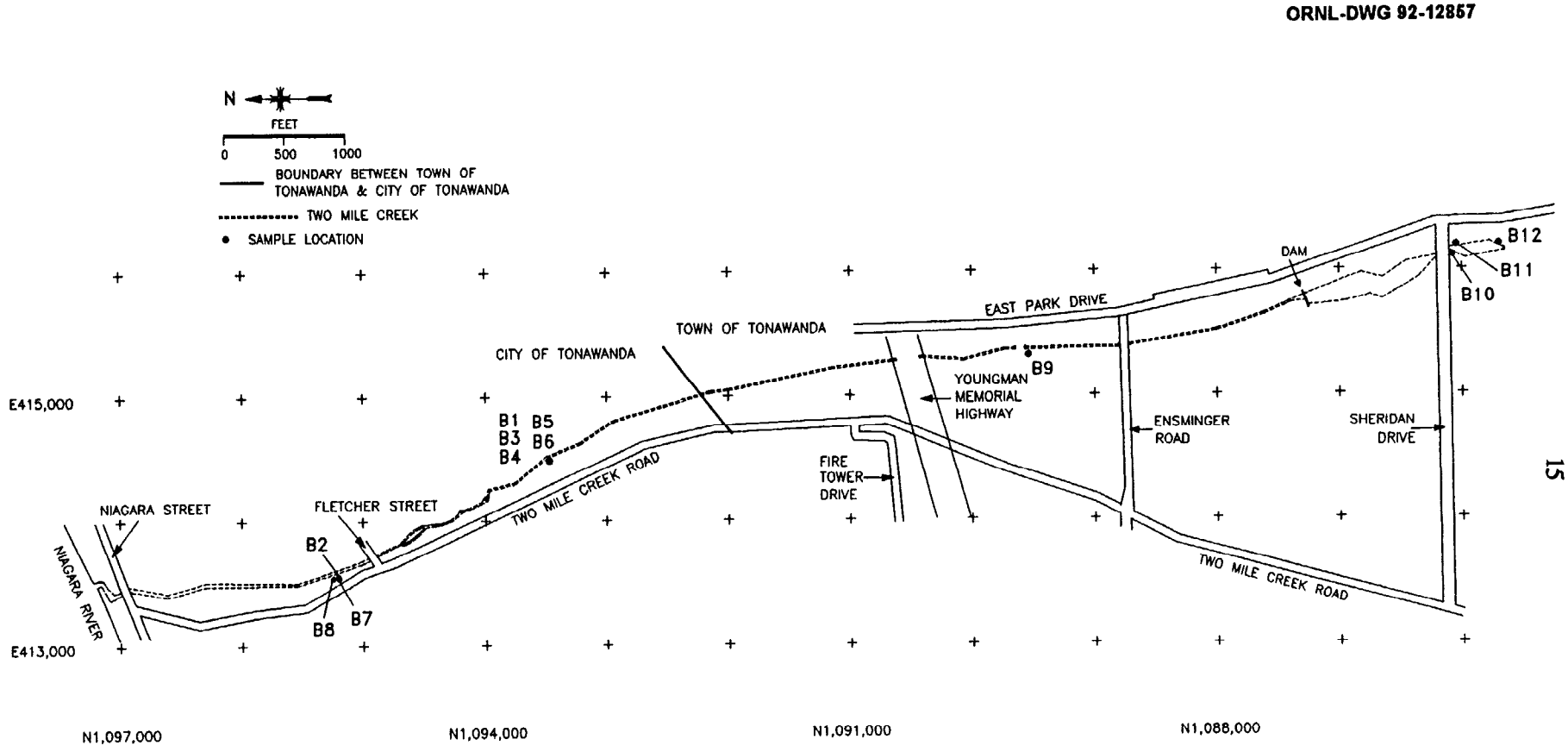

Fig. 12. Diagram showing locations of biased soil samples collected in 1991 at Two Mile Creek.

ORNL-PHOTO 10234-92

Fig. 13. View looking west at area of sample locations B1 and B3–B6.

ORNL-PHOTO 10235-92

Fig. 14. View looking east at sample location B3. Samples B1 and B4–B6 were also collected in this area.

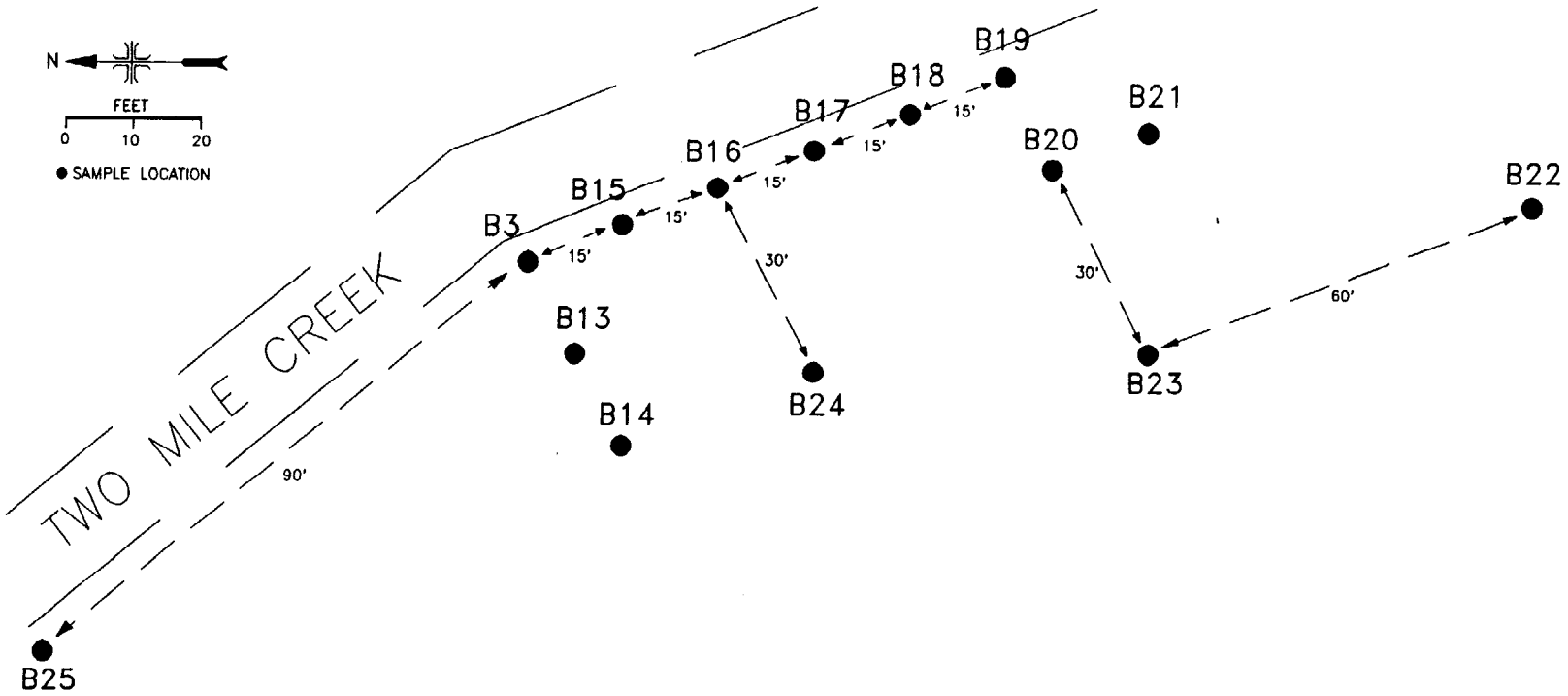

Fig. 15. Diagram showing locations of additional biased soil samples collected in 1996. All 1996 samples are shown relative to sample B3 collected in 1991 (see Fig. 12).

ORNL-DWG 96-7180

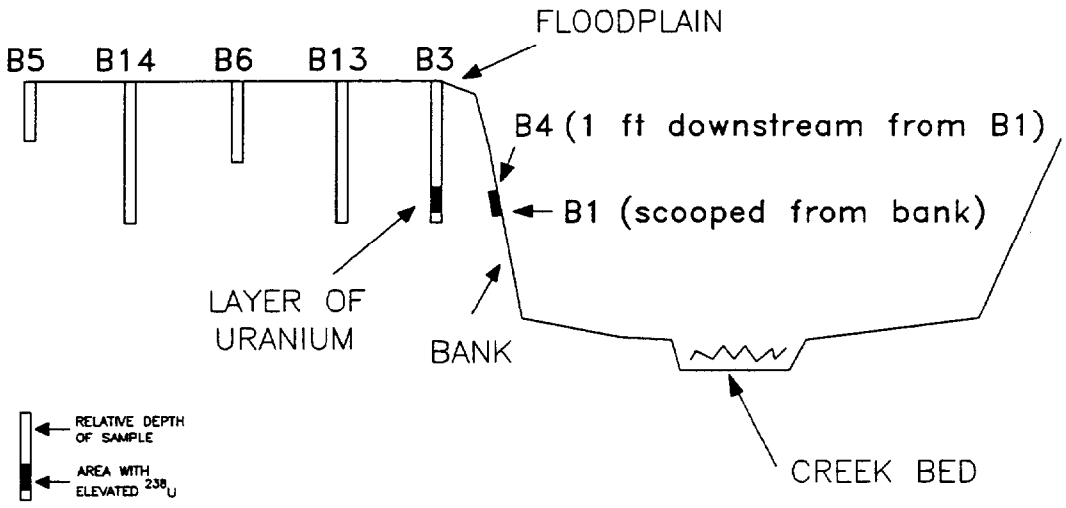

Fig. 16. Cross section of Two Mile Creek showing two 1996 samples in relation to the 1991 samples previously shown in Fig. 11. Diagram not drawn to scale.

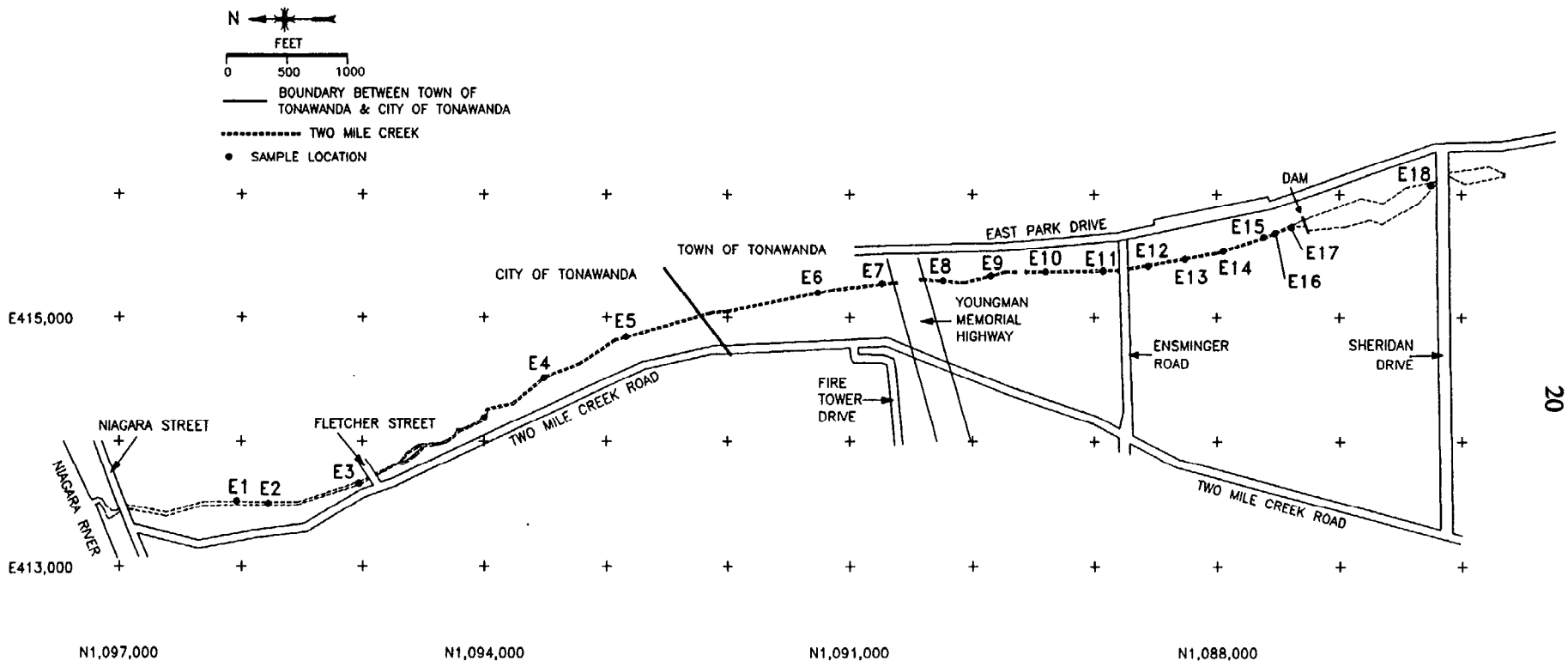

Fig. 17. Diagram showing sampling locations for sediment collected at Two Mile Creek.

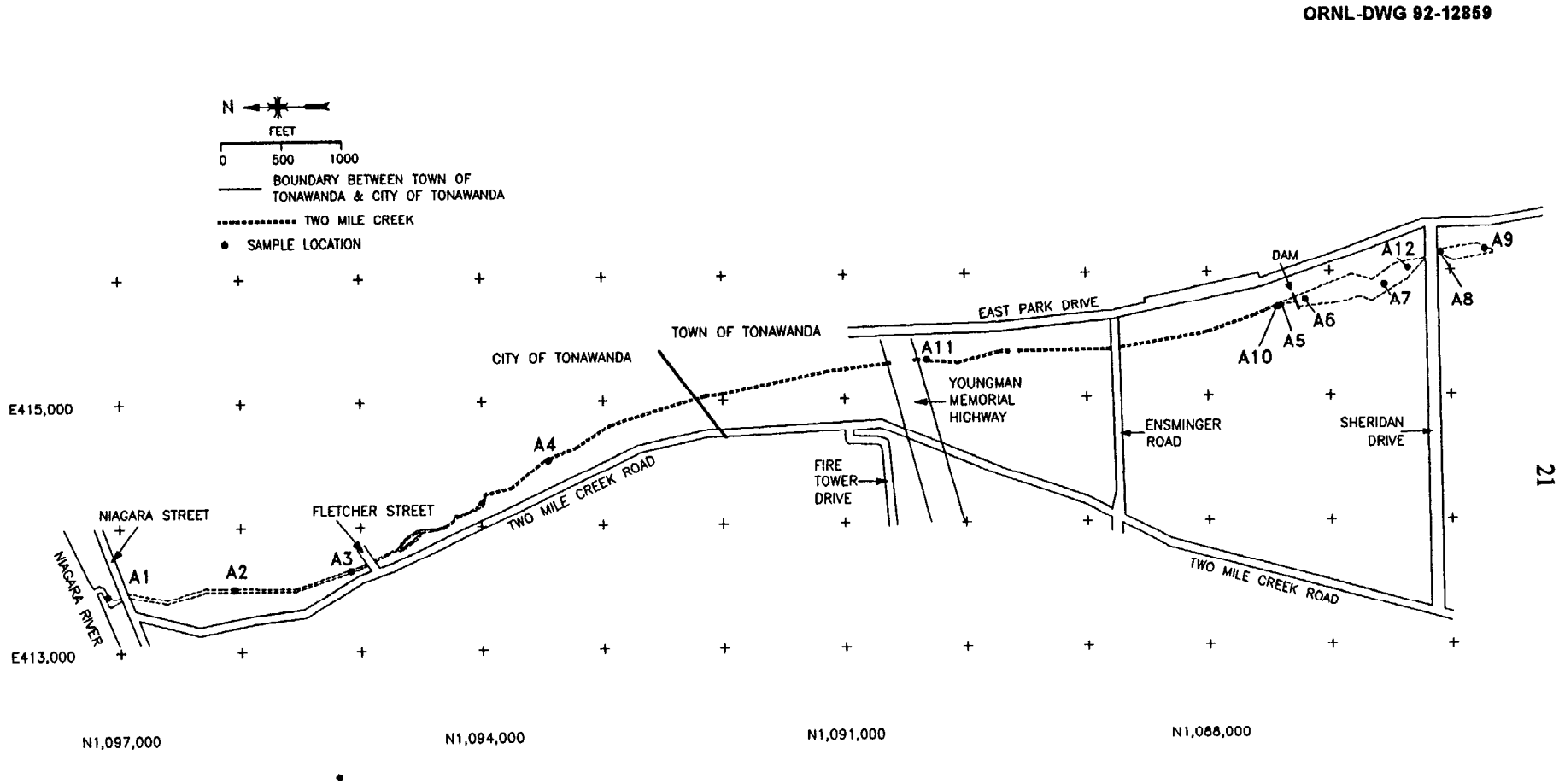

Fig. 18. Diagram showing locations of core samples collected at Two Mile Creek.

Table 1. Applicable guidelines for protection against radiation
(Limits for uncontrolled areas)

Mode of exposure	Exposure conditions	Guideline value
Gamma radiation	Indoor gamma radiation level (above background)	20 μR/h[a]
Radionuclide concentrations in soil (generic)	Maximum permissible concentration of the following radionuclides in soil above background levels, averaged over a 100-m^2 area ^{226}Ra ^{232}Th ^{230}Th	5 pCi/g averaged over the first 15 cm of soil below the surface; 15 pCi/g when averaged over 15-cm-thick soil layers more than 15 cm below the surface
Derived concentrations	Maximum permissible concentration of total uranium in soil above background levels, averaged over a 100-m^2 area.	60 pCi/g[b]
Guideline for non-homogeneous contamination (used in addition to the 100-m^2 guideline)[c]	Applicable to locations with an area $\leq$25 m^2, with significantly elevated concentrations of radionuclides ("hot spots")	$G_A = G_i(100/A)^{1/2}$, where G_A = guideline for "hot spot" of area (A) G_i = guideline averaged over a 100-m^2 area

[a]The 20 μR/h shall comply with the basic dose limit (100 mrem/year) when an appropriate-use scenario is considered.

[b]DOE guidelines for uranium are derived on a site-specific basis. A total uranium guideline of 60 pCi/g will be applied at the Two Mile Creek site. This corresponds to a ^{238}U concentration of ~30 pCi/g.

[c]DOE guidelines specify that every reasonable effort shall be made to identify and to remove any source that has a concentration exceeding 30 times the guideline value, irrespective of area (adapted from *Revised Guidelines for Residual Radioactive Material at FUSRAP and Remote SFMP Sites*, April 1987).

Sources: Adapted from U.S. Department of Energy, DOE Order 5400.5, April 1990; U.S. Department of Energy, *Guidelines for Residual Radioactive Material at Formerly Utilized Sites Remedial Action Program and Remote Surplus Facilities Management Program Sites*, Rev. 2, March 1987; and U.S. Department of Energy, *Radiological Control Manual*, DOE/EH-0256T (DOE N 5480.6), June 1992.

Table 2. Background radiation levels and concentrations of selected radionuclides in soil near Tonawanda, New York

Type of radiation measurement or sample	Radiation level or radionuclide concentration	
	Range	Average
Gamma exposure rate at ground surface (μR/h)[a]	8–11	9
Concentration of radionuclides in soil (pCi/g)[a]		
^{238}U	0.8–1.1	1.0
^{226}Ra	0.7–1.1	0.9
^{232}Th	0.5–0.9	0.8

[a]Values obtained from four locations in the Tonawanda area.

Source: R. E. Rodriguez, M. E. Murray, and M. S. Uziel, *Results of the Radiological Survey at the Town of Tonawanda Landfill, Tonawanda, New York (TNY001)*, ORNL/RASA-92/12, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., October 1992.

Table 3. Concentrations of radionuclides in soil, sediment, and core samples from Two Mile Creek, Tonawanda, New York

Sample Id[a]	Depth (cm)	Radionuclide concentration (pCi/g)[b]		
		^{238}U	^{226}Ra	^{232}Th
		Biased soil samples—1991[c]		
B1	0–1	18 ± 3	15 ± 0.2	0.99 ± 0.1
B1B	1–15	16 ± 1	5.4 ± 0.06	0.98 ± 0.07
B2	0–15	1.6 ± 0.9	0.90 ± 0.03	1.1 ± 0.05
B2R[d]	*e*	220 ± 40	190 ± 1	340 ± 2
B3A	0–15	1.8 ± 0.9	1.0 ± 0.03	0.79 ± 0.04
B3B	15–30	2.7 ± 1	1.1 ± 0.03	0.93 ± 0.04
B3C	30–45	3.3 ± 1	1.4 ± 0.03	1.1 ± 0.05
B3D	45–60	5.9 ± 1	1.6 ± 0.05	1.2 ± 0.07
B3E[f]	60–75	21 ± 2	16 ± 0.2	0.99 ± 0.1
B3F	75–90	37 ± 2	8.7 ± 0.2	1.0 ± 0.2
B3G	90–105	20 ± 4	2.6 ± 0.09	1.0 ± 0.1
B4A	0–15	25 ± 1	25 ± 0.1	0.95 ± 0.06
B4B	15–30	21 ± 3	5.9 ± 0.1	0.97 ± 0.1
B5A	0–15	1.8 ± 0.6	1.1 ± 0.03	0.87 ± 0.04
B5B	15–30	3.9 ± 2	1.4 ± 0.05	1.1 ± 0.06
B5C	30–45	4.0 ± 0.5	1.1 ± 0.02	0.89 ± 0.03
B5D	45–60	3.1 ± 1	0.92 ± 0.03	0.92 ± 0.1
B6A	0–15	1.2 ± 0.9	1.3 ± 0.04	1.0 ± 0.05
B6B	15–30	2.6 ± 0.8	1.6 ± 0.04	1.1 ± 0.05
B6C	30–45	4.2 ± 1	1.8 ± 0.04	1.1 ± 0.06
B7R[d]	0–15	400 ± 100	390 ± 2	290 ± 3
B8	0–15	2.4 ± 0.8	1.9 ± 0.02	1.2 ± 0.03
B9A	0–15	3.6 ± 0.9	2.8 ± 0.04	2.6 ± 0.06
B9B	15–30	3.3 ± 1	3.0 ± 0.05	2.8 ± 0.2
B9C	30–45	3.3 ± 1	3.2 ± 0.04	3.1 ± 0.06
B10A	0–15	1.3 ± 0.5	1.2 ± 0.02	0.93 ± 0.03
B10B	15–30	1.8 ± 0.5	1.2 ± 0.02	0.95 ± 0.03
B11A	0–15	1.7 ± 0.8	1.0 ± 0.02	0.88 ± 0.04
B11B	15–30	1.8 ± 1	1.3 ± 0.02	1.1 ± 0.04
B11C	30–45	2.1 ± 0.5	1.9 ± 0.03	1.3 ± 0.03
B11D	45–60	2.1 ± 1	1.6 ± 0.03	1.2 ± 0.05
B12A	0–15	1.8 ± 0.9	0.96 ± 0.03	0.97 ± 0.05
B12B	15–30	<2.0	1.0 ± 0.02	1.1 ± 0.04
B12C	30–45	2.6 ± 1	1.2 ± 0.03	1.0 ± 0.04
B12D	45–60	9.0 ± 2	1.5 ± 0.05	1.1 ± 0.07
B12E	60–75	15 ± 2	3.0 ± 0.05	0.94 ± 0.05

Table 3 (continue)

Sample Id[a]	Depth (cm)	Radionuclide concentration (pCi/g)[b]		
		^{238}U	^{226}Ra	^{232}Th
		Biased soil samples—1996[c]		
B13C	30–45	3.1 ± 1	1.2 ± 0.1	0.88 ± 0.2
B13D	45–60	2.4 ± 0.4	0.75 ± 0.09	0.74 ± 0.1
B13E	60–75	1.5 ± 0.4	0.74 ± 0.06	0.78 ± 0.1
B13F	75–90	1.2 ± 0.3	0.77 ± 0.06	0.79 ± 0.1
B13G	90–105	1.2 ± 0.6	0.85 ± 0.09	0.86 ± 0.1
B14C	30–45	3.1 ± 1	1.6 ± 0.1	1.1 ± 0.2
B14D	45–60	2.1 ± 0.4	0.92 ± 0.09	1.0 ± 0.2
B14E	60–75	1.8 ± 0.4	0.77 ± 0.08	0.91 ± 0.1
B14F	75–90	<1.6	0.73 ± 0.07	0.77 ± 0.1
B14G	90–105	<1.9	0.86 ± 0.1	0.81 ± 0.2
B15C	30–45	4.3 ± 0.6	1.0 ± 0.1	1.0 ± 0.2
B15D[g]	45–60	5.2 ± 2	2.0 ± 0.2	1.1 ± 0.2
B15E	60–75	4.7 ± 0.6	1.1 ± 0.1	1.1 ± 0.2
B15F	75–90	1.5 ± 0.8	0.75 ± 0.08	0.76 ± 0.1
B15G	90–105	1.1 ± 0.3	0.86 ± 0.2	0.92 ± 0.1
B16A	0–15	1.8 ± 0.4	1.1 ± 0.2	0.98 ± 0.1
B16B	15–30	1.9 ± 1	1.3 ± 0.1	1.1 ± 0.2
B16C	30–45	3.6 ± 0.6	1.4 ± 0.2	1.1 ± 0.2
B16D	45–60	6.7 ± 2	1.1 ± 0.08	0.64 ± 0.1
B16E	60–75	2.7 ± 0.4	0.98 ± 0.08	0.89 ± 0.1
B16F	75–90	1.6 ± 0.4	0.64 ± 0.2	0.50 ± 0.08
B16G	90–105	0.90 ± 0.5	0.66 ± 0.07	0.69 ± 0.1
B17C	30–45	3.3 ± 0.5	1.3 ± 0.1	0.97 ± 0.2
B17D	45–60	3.7 ± 2	1.3 ± 0.1	1.0 ± 0.1
B17E	60–75	8.3 ± 3	1.7 ± 0.1	0.86 ± 0.1
B17F	75–90	4.6 ± 0.5	0.96 ± 0.1	0.81 ± 0.2
B17G	90–105	1.0 ± 0.5	0.71 ± 0.06	0.59 ± 0.1
B18C	30–45	2.4 ± 0.5	1.2 ± 0.1	1.0 ± 0.2
B18D	45–60	5.5 ± 0.9	1.4 ± 0.1	1.3 ± 0.1
B18E	60–75	14 ± 5	4.7 ± 0.3	0.80 ± 0.2
B18F	75–90	11 ± 4	1.8 ± 0.1	1.1 ± 0.2
B19C	30–45	1.1 ± 1	1.1 ± 0.1	0.82 ± 0.1
B19D	45–60	5.1 ± 2	1.5 ± 0.1	1.2 ± 0.2
B19E	60–75	14 ± 4	4.9 ± 0.3	1.0 ± 0.2
B19F	75–90	12 ± 4	2.0 ± 0.1	0.79 ± 0.1
B19G	90–105	5.6 ± 0.6	1.1 ± 0.09	0.82 ± 0.1

Table 3 (continue)

Sample Id[a]	Depth (cm)	Radionuclide concentration (pCi/g)[b]		
		^{238}U	^{226}Ra	^{232}Th
B20C	30–45	4.1 ± 2	1.3 ± 0.1	1.0 ± 0.1
B20D	45–60	6.3 ± 0.7	2.5 ± 0.1	1.1 ± 0.1
B20E	60–75	23 ± 7	3.5 ± 0.2	1.1 ± 0.1
B20F	75–90	15 ± 1	1.1 ± 0.08	0.93 ± 0.1
B21C	30–45	3.9 ± 2	1.3 ± 0.1	1.0 ± 0.1
B21D	45–60	10 ± 0.8	3.7 ± 0.2	0.86 ± 0.2
B21E	60–75	6.2 ± 2	1.4 ± 0.1	0.97 ± 0.2
B21F	75–90	4.7 ± 2	1.0 ± 0.09	0.90 ± 0.1
B21G	90–105	2.4 ± 0.4	0.87 ± 0.07	0.91 ± 0.1
B22D	45–60	3.1 ± 0.5	1.3 ± 0.1	1.1 ± 0.1
B22E	60–75	5.5 ± 2	1.9 ± 0.1	0.97 ± 0.2
B22F	75–90	10 ± 1	3.2 ± 0.2	0.91 ± 0.1
B22G	90–105	6.0 ± 0.6	0.99 ± 0.09	0.74 ± 0.1
B23C	30–45	3.8 ± 1	1.4 ± 0.1	1.2 ± 0.2
B23D	45–60	5.3 ± 2	2.2 ± 0.1	1.0 ± 0.1
B23E	60–75	5.5 ± 2	1.1 ± 0.09	0.89 ± 0.1
B23F	75–90	3.4 ± 1	0.82 ± 0.07	0.88 ± 0.1
B23G	90–105	2.5 ± 1	0.70 ± 0.07	0.83 ± 0.1
B24C	30–45	2.1 ± 0.4	1.1 ± 0.09	0.90 ± 0.1
B24D	45–60	2.4 ± 1	0.89 ± 0.07	0.84 ± 0.09
B24E	60–75	0.75 ± 0.2	0.83 ± 0.07	0.79 ± 0.1
B24F	75–90	1.1 ± 0.7	0.85 ± 0.08	0.83 ± 0.1
B24G	90–105	0.83 ± 0.5	0.80 ± 0.08	0.81 ± 0.1
B25C	30–45	2.0 ± 0.4	1.4 ± 0.1	1.1 ± 0.1
B25D	45–60	3.3 ± 0.5	1.5 ± 0.1	1.2 ± 0.1
B25E	60–75	8.3 ± 3	3.3 ± 0.2	1.1 ± 0.1
B25F	75–90	8.3 ± 3	1.5 ± 0.1	0.97 ± 0.2
		Sediment samples—1991[h]		
E1	*e*	<2.7	0.63 ± 0.04	0.50 ± 0.07
E2	*e*	2.8 ± 2	0.62 ± 0.08	0.44 ± 0.2
E3	*e*	1.1 ± 0.3	0.82 ± 0.02	0.61 ± 0.03
E4	*e*	0.68 ± 0.6	0.57 ± 0.02	0.49 ± 0.02
E5	*e*	1.7 ± 0.8	0.95 ± 0.03	0.90 ± 0.05
E6	*e*	6.5 ± 2	0.90 ± 0.04	0.70 ± 0.1
E7	*e*	2.1 ± 0.8	0.59 ± 0.02	0.36 ± 0.02
E8	*e*	2.2 ± 0.6	1.7 ± 0.4	1.0 ± 0.4

Table 3 (continue)

Sample Id[a]	Depth (cm)	Radionuclide concentration (pCi/g)[b]		
		^{238}U	^{226}Ra	^{232}Th
E9	*e*	1.2 ± 0.6	0.72 ± 0.01	0.47 ± 0.03
E10	*e*	0.87 ± 0.6	0.55 ± 0.01	0.34 ± 0.02
E11	*e*	1.4 ± 0.4	0.73 ± 0.02	0.49 ± 0.02
E12	*e*	2.1 ± 0.8	0.65 ± 0.02	0.46 ± 0.03
E13	*e*	1.0 ± 0.5	0.73 ± 0.02	0.47 ± 0.02
E14	*e*	1.2 ± 0.6	0.69 ± 0.02	0.45 ± 0.03
E15	*e*	1.3 ± 0.6	0.75 ± 0.02	0.47 ± 0.02
E16	*e*	1.1 ± 0.3	0.74 ± 0.01	0.42 ± 0.02
E17	*e*	0.92 ± 0.3	0.77 ± 0.02	0.43 ± 0.02
E18	*e*	1.6 ± 1	1.1 ± 0.03	0.89 ± 0.04
		Core samples—1991[i]		
A1A	0–15	1.8 ± 0.5	0.94 ± 0.02	0.69 ± 0.03
A1B	15–30	2.8 ± 1	0.97 ± 0.03	0.66 ± 0.05
A1C	30–45	5.0 ± 1	1.2 ± 0.03	0.96 ± 0.05
A1D	45–60	3.5 ± 0.5	1.1 ± 0.02	0.74 ± 0.03
A1E	60–75	5.3 ± 0.9	0.73 ± 0.02	0.45 ± 0.04
A2A	0–20	0.89 ± 0.3	0.55 ± 0.01	0.42 ± 0.02
A2B	20–35	2.4 ± 1	0.67 ± 0.02	0.71 ± 0.04
A3A	0–15	1.6 ± 0.5	0.76 ± 0.02	0.66 ± 0.02
A3B	15–30	2.0 ± 1	0.97 ± 0.02	0.98 ± 0.03
A3C	30–45	<1.8	0.69 ± 0.02	0.66 ± 0.02
A4A	0–15	1.4 ± 0.9	0.83 ± 0.02	0.92 ± 0.03
A4B	15–30	1.6 ± 0.9	0.85 ± 0.02	0.88 ± 0.03
A5A	0–20	1.5 ± 0.7	0.70 ± 0.02	0.50 ± 0.03
A5B	20–40	2.5 ± 0.9	0.68 ± 0.02	0.68 ± 0.04
A6A	0–15	1.8 ± 0.8	0.99 ± 0.03	0.92 ± 0.05
A6B	15–30	1.9 ± 0.6	1.1 ± 0.02	0.97 ± 0.04
A6C	30–45	1.3 ± 0.6	1.1 ± 0.03	0.95 ± 0.04
A6D	45–60	<1.9	0.94 ± 0.02	0.94 ± 0.03
A6E	60–75	2.1 ± 0.9	0.87 ± 0.02	0.92 ± 0.03
A7A	0–15	2.2 ± 2	1.4 ± 0.03	1.2 ± 0.06
A7B	15–30	1.6 ± 0.9	1.3 ± 0.03	1.1 ± 0.05
A7C	30–45	2.0 ± 1	1.1 ± 0.03	1.0 ± 0.04
A7D	45–60	1.7 ± 0.8	0.80 ± 0.02	0.83 ± 0.04

Table 3 (continue)

Sample Id[a]	Depth (cm)	Radionuclide concentration (pCi/g)[b]		
		^{238}U	^{226}Ra	^{232}Th
A8A	0–20	1.8 ± 1	0.98 ± 0.02	0.83 ± 0.03
A8B	20–35	1.2 ± 0.7	1.2 ± 0.03	0.98 ± 0.04
A8C	35–55	1.2 ± 0.9	0.99 ± 0.03	0.94 ± 0.04
A9	0–20	1.4 ± 0.7	1.1 ± 0.05	0.87 ± 0.04
A10A	0–20	1.0 ± 0.4	0.75 ± 0.02	0.45 ± 0.02
A10B	20–35	<1.3	0.60 ± 0.02	0.48 ± 0.03
A10C	35–55	1.2 ± 0.8	0.88 ± 0.02	0.93 ± 0.04
A11A	0–10	<1.4	0.73 ± 0.02	0.47 ± 0.03
A11B	10–25	1.3 ± 0.9	0.67 ± 0.03	0.54 ± 0.05
A12A	0–15	2.8 ± 2	1.1 ± 0.03	0.88 ± 0.04
A12B	15–30	3.5 ± 2	1.2 ± 0.03	0.92 ± 0.05
A12C	30–45	<1.4	0.84 ± 0.02	0.78 ± 0.03
A12D	45–60	1.2 ± 0.4	0.82 ± 0.02	0.85 ± 0.03

[a]Sample locations are shown on Figs. 11, 12, 15, 16, 17, and 18.
[b]Indicated counting error is at the 95% confidence level (±2σ).
[c]Biased samples are taken from areas shown to have elevated gamma exposure rates.
[d]Rock portion of sample.
[e]Not applicable.
[f]Sample B3E contained 19 ± 3 pCi/g ^{230}Th.
[g]Sample B15D contained 3.4 ± 0.6 pCi/g ^{230}Th.
[h]Sediment samples contained 4 to 6 in. of sediment scooped from the middle of Two Mile Creek.
[i]Each core sample was collected by driving a section of pipe (2.5 in. diameter) down into the creek bottom as far as possible (to refusal).

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