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Environmental effects of produced waters
at oilfield production sites in the Big Sinking Creek
and Schumaker Ridge areas,
Lee County, Kentucky

By

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ABSTRACT

During July of 1995 and June of 1996, thirteen oilfield production sites in the Big Sinking Creek and Schumaker Ridge areas of northern Lee County in eastern Kentucky were visited to determine if produced waters and produced water solids had impacted sites in this area. Salt-scarred areas at oilfield production sites in this area were found to be relatively restricted in size, not very deeply eroded compared to sites in the midwest and southwest, and to have revegetated fairly quickly, probably because of the high rainfall and rapid flushing of salts from the root zone of plants. Saline groundwater still remains in the shallow subsurface beneath small barren areas at some sites. Areas of barren or sparse vegetation at some sites were found to be underlain by oil-saturated soil at shallow depths suggesting that the oil inhibits plant growth. Seepage of brine at one site has raised stream conductivities about 35-45 percent higher than values just upstream.

Five sites have slightly anomalous concentrations of copper, lead, and zinc in soils containing tank sludge. Two samples from one site have high levels of radium (1770-3390 pCi/g), copper (165-195 ppm), and lead (200-245 ppm). These two samples have high concentrations of barium and strontium and low concentrations of zirconium suggesting that they are composed mostly of solids from tank sludge and that barite is present in high concentrations. The lead levels in these two samples are below action levels used for Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA) sites (400 ppm).

Radiometric surveys and radiochemical analyses determined that 9 of 13 sites have high radioactivity and radium in equipment, soils, and wetland sediments. Moderate levels occur at 2 sites and low levels occur at 2 sites. Radium-rich tank sludge, soils, and sediments are widespread at one site at the northern end of Lake Zachariah. Sites with high radioactivity in equipment or high radium activity in soils would be Naturally Occurring Radioactive Material (NORM)-contaminant sites under the least conservative state regulations proposed or in place. The State of Kentucky does not presently have NORM regulations.

Dispersion of radium is occurring in two ways: 1) by the movement of radium-bearing solids (mostly barite), and 2) movement of dissolved radium in water. Iron oxyhydroxide precipitates are forming in the seep zone in a small wetland downslope from a tank battery at one site. These precipitates are radioactive and the iron oxyhydroxides are probably adsorbing dissolved radium from the ground water. Elsewhere at this same site, radium-bearing barite is accumulating at the edge of and probably within the wetland at the toe of the slope below a large area of radium-enriched soils.

INTRODUCTION

These investigations in Lee County in eastern Kentucky (Fig. 1A) are part of a study of the effects of produced waters on soils, shallow bedrock, surface waters, and shallow ground waters being conducted by the U.S. Geological Survey. Waters produced with oil and gas commonly have high total dissolved solids (as much as 40 percent). In addition to high concentrations of sodium, chloride, and other major elements, produced waters and solids formed from these waters contain naturally occurring radioactive materials (NORM) and trace elements such as arsenic, selenium, cadmium, chromium, copper, lead, nickel, silver, zinc, mercury, bromine, iodine, fluorine, lithium, and boron (Kraemer and Reid, 1984; Collins, 1975; Saunders and Swann, 1990; Jacobs and others, 1992). Recognized effects of high-salinity produced waters include the death of vegetation ("salt scarring") and contamination of aquifers and surface water by salt. Loss of vegetation can result in increased soil erosion and siltation of streams, lakes, and reservoirs. Contamination of soil, sediment, and water by NORM and trace elements is also possible.

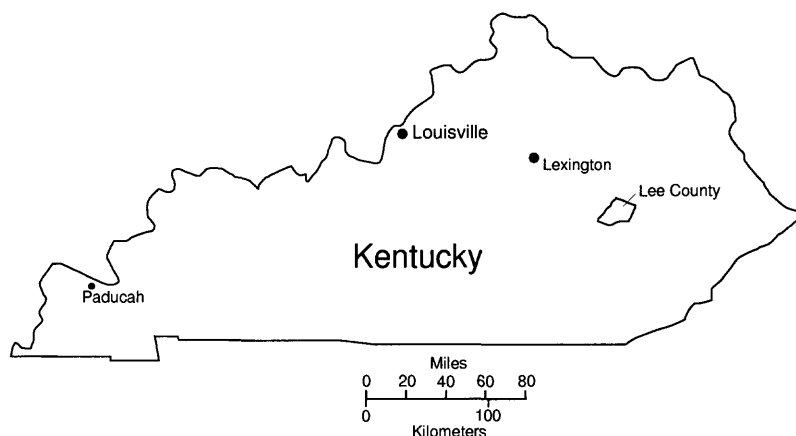


Figure 1A- Location map for Lee County, eastern Kentucky.

The Big Sinking Creek oilfield was discovered in 1917 or 1918. Historic production exceeds 80 million barrels making it one of the largest fields in the Kentucky portion of the Appalachian Basin (Brandon Nuttall, Kentucky Geological Survey, written commun., 1997). The Big Sinking Creek area lies in a maturely dissected plateau with narrow ridge crests separated by steeply sloped, heavily forested valleys. This rugged topography made early development of the field difficult (Jones and McFarlan, 1933). Production is from middle Silurian dolostones of the Lockport Dolomite and from the "Big Six" sandstone (Black, 1978). A high grade crude known as "Somerset light" is produced. It brought premium prices in the early days of the field. Waterflooding started in 1949 and by 1964 about 5500 acres of leases were under active water injection (Stack, 1965). Present

production is mostly from wells that produce small amounts of oil ("stripper wells").

Early in the history of waterflooding it was recognized that surface water and shallow formation water supplies were inadequate and several small reservoirs were constructed by the operators to hold surface runoff and produced waters for reinjection into the producing zones (Fig. 1B). The largest of these reservoirs (about 1 mile from the dam to the inlet) is located along the Zachariah fork of Big Sinking Creek and is known locally as Lake Zachariah. Freeman (1941) reports a single brine analysis from the Big Sinking field in Lee County. Total dissolved solids (TDS) are 90,690 ppm and the brine is a Na-Ca-Cl type.

Radioactivity on oilfield equipment was first noted in the Big Sinking Creek oilfield during informal surveys conducted by the Kentucky Division of Water (Sam Lester, written commun., 1995). Contamination of surface waters in Big Sinking Creek and its tributaries with constituents derived from oilfield brines was observed during studies of water quality in three watersheds in the Kentucky River drainage basin (Evaldi and Kipp, 1991). Loss of biologic diversity in Big Sinking Creek has been attributed to oil-field brines (Logan and others, 1989). The algal flora have been reduced and are dominated by species that tolerate saline conditions (Logan and others, 1989). Macroinvertebrate fauna have been reduced in number and species, indicating toxic conditions (Logan and others, 1989). Fish fauna have been dramatically reduced and immediately below Lake Zachariah they were entirely eliminated (Logan and others, 1989).

This report documents the results of our reconnaissance studies at 13 oilfield production sites in the Big Sinking Creek and Schumaker Ridge areas of northern Lee County in eastern Kentucky (Fig. 1B).

SURVEY AND SAMPLING METHODS

Field descriptions of all sites were recorded. Detailed maps for sites LC95-1 and LC95-6 were created with tape and compass with supplemental distance and direction measurements made by pace and compass from established survey stations. Features at site LC95-2 are from a field sketch and all distances are approximate. A map of the location of site LC95-1 was based on a color-infrared aerial photo.

Field measurements of water samples included temperature, pH, and conductivity. Unfiltered water samples were collected in the field in one liter polyethylene bottles. These bottles were prerinsed with sampled water prior to filling. The samples were transported back to the laboratory in an iced cooler and then stored in a laboratory refrigerator for analysis a few weeks later. In the laboratory, an aliquot of the sample was removed and an alkalinity titration using standard sulfuric acid was performed. The alkalinity in the lab may not reflect the actual *in situ* alkalinity since bacterial activity may have modified the samples. In the lab, the remaining sample was filtered through a 0.45 micron polycarbonate membrane and one aliquot of the filtrate was acidified to a pH less than 2 using nitric acid for cation

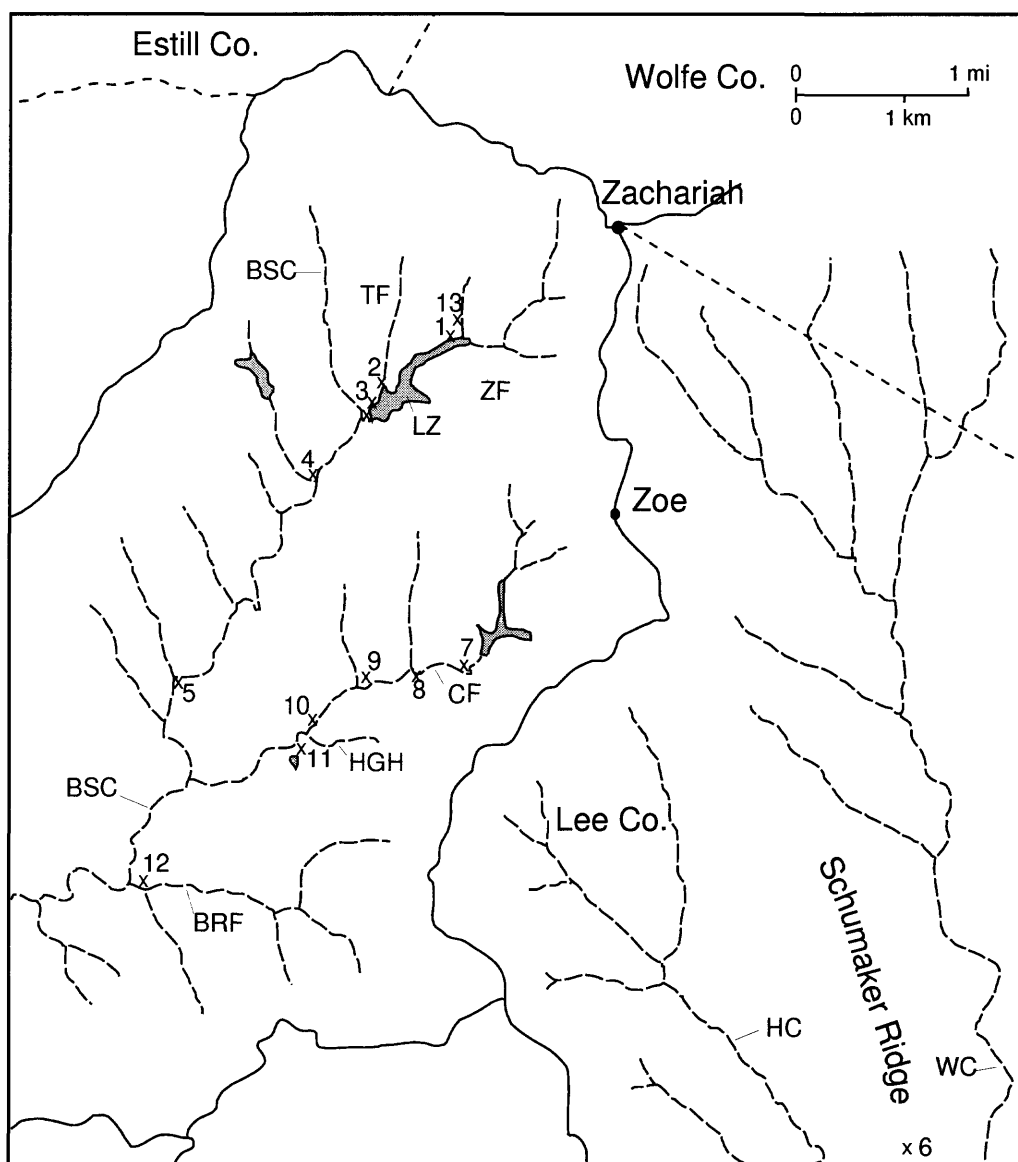


Figure 1B- Location map showing 13 oilfield production sites visited during this study in the Big Sinking Creek and Schumaker Ridge areas of northern Lee County. X- study sites (in the text the sites are designated LC95-1 to LC95-13). Major roads (solid lines), county boundaries (short dash lines), and creeks (long dash lines) are shown. The location of four small brine storage reservoirs is indicated: one upstream from site LC95-4, one adjacent to sites LC95-1,2,3; one adjacent to site LC95-11; and one upstream from site LC95-7. BSC- Big Sinking Creek; BRF- Bald Rock Fork of Big Sinking Creek ; ZF- Zachariah Fork of Big Sinking Creek; LZ- Lake Zachariah; TF- Townshend Fork of Big Sinking Creek; CF- Caves Fork of Big Sinking Creek; HGH- Hog Gap Hollow; HC- Hell Creek; WC- Walker Creek.

analysis while a second aliquot of the filtrate was refrigerated prior to analysis for anions. Cations were determined with standard flame atomic absorption spectrophotometry. The method of additions was utilized to compensate for matrix interferences. Anions were measured by ion chromatography following the method of Fishman and Pyen (1979).

Radium-226 in water samples was determined by the radon emanation technique (Broecker, 1965). An aliquot of the sample was placed in a radon bubbler and helium passed through it to remove all radon. The flask was then sealed to allow in-growth of radon-222 from the radium-226 in the sample. After a known time interval, the radon was again removed from the flask and transferred to a counting cell coated with silver-activated zinc sulfide and placed on a photomultiplier tube to measure radon and daughter product activity. The efficiency of the radon collection, transfer, and counting procedures was calibrated using National Institute of Standards and Technology (NIST) radium standards.

Soil samples were collected from the surface layer (10 cm) with a non-metallic scoop and placed in HUBCO sample sacks. Samples were transported to the laboratory where they were dried, disaggregated in a crusher, and split in a riffle splitter. One split was analyzed by non-destructive, energy dispersive, X-ray fluorescence for iron, copper, lead, zinc, cadmium, zirconium, barium, strontium, bromine, and iodine. The samples were not pulverized and homogenized prior to analysis and the results should therefore be considered semi-quantitative.

The radium-226 and radium-228 activity of soil samples was measured using gamma-ray spectroscopy in two different laboratories. To discriminate these data from the GAD-6-spectrometer data, these data will be referred to as "laboratory-based radiochemical data". In laboratory 1, aliquots of samples were sealed in 10 ml polyethylene vials and placed in the well of a high-purity germanium detector which was calibrated with similar quantities of radium-containing barium-sulfate precipitate prepared by adding $\text{Ba}(\text{NO}_3)_2$ to NIST radium-226 and radium-228 standards and then adding H_2SO_4 to quantitatively precipitate $\text{Ba}(\text{Ra})\text{SO}_4$ (Michel et al., 1981). The $\text{Ba}(\text{Ra})\text{SO}_4$ precipitate standards were stored to allow equilibration of daughter products of radium-226 and radium-228 before using the standards to calibrate the detector. BaSO_4 was chosen as the matrix to calibrate the detector because most of the high-activity samples in this study contain radium in a BaSO_4 precipitate, which is common in oil-field brine scales.

Other soil samples were analyzed by gamma-ray spectrometry in a second laboratory (laboratory 2). The samples were sealed in plastic containers and held for 3 weeks prior to counting to permit attainment of radioactive equilibrium between radium-226 and its short-lived daughters. The samples were counted for several hours on a low-energy photon (LEP) detector. Gamma-ray energies ranging from 30 keV to 400 keV were recorded for the analyses. Detector efficiencies were calibrated versus gamma-ray energies using a NIST-traceable source. Radium-228 activities are

reported here using the photopeaks derived from its immediate decay product, actinium-228.

Two samples were analyzed by both laboratories. Radium-226 activities reported by laboratory 2 were consistently higher for both samples. Lab 2 was 40% higher for a high activity sample (a few thousand pCi/g) and 16% higher for a lower activity sample (a few hundred pCi/g). Radium-228 activities reported by the two laboratories for the two samples did not vary systematically. Lab 2 was 48% higher for the higher activity sample, but 14% lower for the lower activity sample.

Each site was surveyed using a handheld Geometrics scintillometer (Model Exploranium, range 1-10,000 counts per second, cps). (Note- Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government). μ R meters record data that are more useful in determining radiation exposure. However, the μ R instrument taken to the field in 1995 failed during the first day of use. In 1996, a field calibration of the Geometrics scintillometer used during the 1995 survey with a calibrated Ludlum Model 12S μ R meter was completed. This calibration showed a nonlinear relation defined as $x(\mu\text{R/hr}) = 2.2 + 0.18492 y - 1.3428 \times 10^{-5} y^2$ where y is the scintillometer reading in counts per second (cps) (J.K. Otton, unpublished data, 1996). The scintillometer data are reported here in the text in cps with equivalent μ R/hr calculated readings given in parentheses. "Background" scintillometer readings for sites examined by the U.S. Geological Survey in eastern Kentucky ("background" here defined as readings on apparently undisturbed soils at the periphery of the site) ranged from 25-35 cps (7-8 μ R/hr).

Produced water and oil storage tanks, separator tanks, heater/treater tanks, flow lines, pumping wellheads, and injection wellheads were examined by placing the detector flush against the surface of the equipment. Soil surfaces, bedrock exposed in salt scars, and disturbed, oily, and discolored soils also were examined in a similar manner.

Soils at five sites (LC95-1,2,6,7,13) were surveyed in the field with a Scintrex GAD-6 gamma spectrometer. Data from this instrument will hereafter be referred to as "GAD-6 spectrometer data" or a similar expression. This instrument is a four-channel analyzer that records total gamma counts (over an energy range of 0.40-2.8 Mev) and gamma counts for three windows: a potassium window (1.35-1.60 Mev), a uranium window (1.60-1.85 Mev), and a thorium window (2.50-2.75 Mev). The potassium window brackets the 1.46 Mev potassium-40 peak, the uranium window brackets the 1.76 Mev bismuth-214 peak (a uranium-238 decay product), and the thorium window brackets the 2.62 Mev thallium-208 peak (a thorium-232 decay product). The recorded count data for the bismuth-214 and thallium-208 channels are considered to approximate equilibrium activity of radium-226 and radium-228, unless there is suspicion of substantial loss of radon (radon-222 or radon-220) from the material being measured. For oilfield brine solids, the emanation of radon from the solids typically averages less than 5

percent (Hebert, Scott, and Zrake, 1995; Rood and Kendrick, 1996); thus, radon loss is not considered significant.

Where uranium and thorium are believed to be present, the GAD-6-spectrometer raw count data are converted to equivalent uranium-238 (parts per million eU), and equivalent thorium-232 (parts per million eTh) using equations that account for the counting efficiency of the instrument and background gamma rays from cosmic sources. These equations are developed uniquely for each instrument by calibrating the instrument on concrete pads of known uranium, thorium, and potassium concentrations and by measuring background cosmic radiation at a site remote from sources of uranium, thorium, and potassium, typically at least 100 m from shore in the middle of a lake. The calibration equations for this instrument were developed from readings made at Department of Energy calibration pads at the airport in Grand Junction, Colorado. The cosmic background values used for this instrument were determined at Fairfax Lake, Fairfax County, Virginia (altitude about 100 m). eU and eTh are calculated assuming secular equilibrium with radium and its decay products. The instrument is further calibrated on a regular basis to make certain that the gamma-counting windows do not drift with time. This is done by using a thorium source and adjusting the thorium count to maximum values using a calibration dial on the instrument. Based on replicate measurements taken in June of 1996 at five sites in southern Illinois (Table 1 in Otton and others, 1997b), the precision of the eU readings is 12 percent and the precision of the eTh readings is 17 percent.

At NORM contaminant sites such as these in Lee County, uranium and thorium are not in secular equilibrium with their decay products. Ra-226 and Ra-228 derived from the oilfield brines are present unsupported by equivalent amounts of their respective parent radionuclides. To obtain Ra-226 activities from GAD-6-spectrometer eU data, the eU readings in ppm are multiplied by 0.33. To obtain Ra-228 activities from eTh data, the eTh readings are multiplied by 0.11. Total radium activities were obtained by addition of radium-226 and radium-228 activities.

In typical field usage (detector placed against a planar, horizontal soil or rock surface), scintillometers and GAD-6 spectrometers receive most gamma rays from soil within a radius of 30-50 cm depending on the density and composition of the soil and resultant attenuation of the gamma rays. The calculated K, U, Th, Ra-226, and Ra-228 values represent an average for that hemispheric volume of soil. Thus, if a thin surface layer of radium-rich material is underlain by radium-poor materials, the equations used to convert the recorded count from the spectrometer will underestimate the radium content of the surface layer.

The laboratory-based gamma-spectrometry technique differs from the field gamma (GAD-6) spectrometry in that a high-resolution Ge(Li) crystal is used rather than a NaI(Tl) crystal. The Ge(Li) crystal volume is much higher than the NaI(Tl) crystal volume. This allows for greater precision. The samples are much smaller and perhaps less representative of the soil at the site.

Soil conductivity measurements were made at Sites LC95-1 and LC95-6 using an EM-31 Geonics Limited instrument (McNeill, 1980a, 1980b). Measurements were made in four orientations: 1) vertical dipole mode parallel to traverse line; 2) vertical dipole mode perpendicular to traverse line; 3) horizontal dipole mode parallel to traverse line; and 4) horizontal dipole mode perpendicular to the traverse line. In the vertical dipole mode, the instrument has an effective depth of exploration of about 6 m whereas in the horizontal dipole mode, the effective depth of exploration is about 3 m. Measurements parallel and perpendicular to the traverse line permit the operator to determine if cultural features such as pipelines may be present that may affect the conductivity readings. Readings more than 10-20 percent different from one another suggest that such features are present.

RESULTS

Thirteen sites in northern Lee County were visited in early July 1995 (Fig. 1B); one site (LC95-1) was revisited in June of 1996. Twelve sites were located within the Big Sinking oilfield; one site along Schumaker Ridge (LC95-6) in a minor oilfield to the southeast of the Big Sinking Creek area. The main oilfield lies within the drainage basin of Big Sinking Creek from which it derives its name. Abandoned oilfield equipment is present at many sites. Abandoned or reclaimed brine pits are present at some sites. The reclaimed pits typically have been filled in by soil from the site.

LC95-1

Site description

Site LC95-1 is located in NW/4, SW/4, NW/4, sec 35, T22N, R10E. It includes two bermed tank batteries, two isolated tanks, an active (1996) pumping unit, and a shed located on a hillslope near the northeastern end of Lake Zachariah (Figs 1B, 2A, 2B). The adjacent floodplain of the Zachariah Fork of Big Sinking Creek includes a brine pond which has a wetland (*Typhae*) occupying its southwestern and northeastern ends. Wetland vegetation expanded into the pond shallows several meters between our 1995 and 1996 visits. The brine pond is separated from the creek by a manmade levee (Fig. 2A). A barren patch of mud lies at the edge of the brine pond and wetland below the lower tank battery (Fig. 2B). A small tributary stream flows along the western edge of the site and enters the wetland west of the pond (Fig. 2B, 2C).

Auger holes and small pits along the northwestern margin of the brine pond suggest that the brine pond is underlain by a layer of oil and oily clay. One pit in the wetland near the small stream inlet at the west end of the pond encountered 70 cm of oily clay without reaching the base.

The upper tank battery is on the hillslope in a graded cut and fill site (Fig. 2B). Shale from the road cut was used to fill and level the tank battery site. As the layer of shale chips covers previously disturbed soil, it seems likely that two or more generations of tank batteries were installed at this site. The lower tank battery lies at the bottom of the slope. The hillslope between the two tank batteries is grassy with many areas of sparse

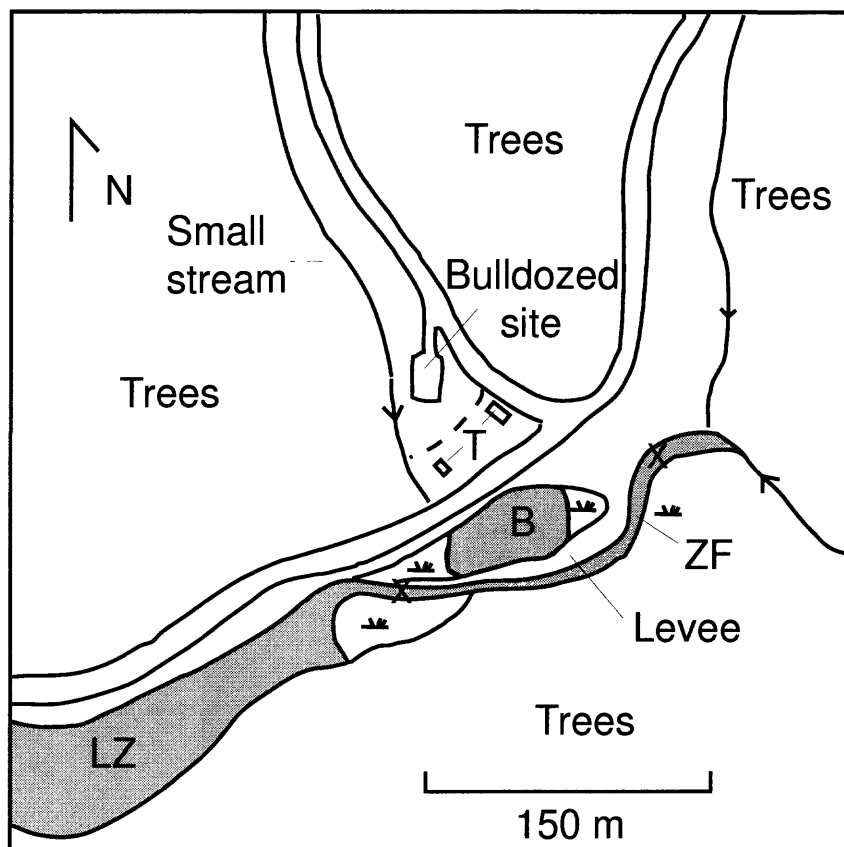


Figure 2A- Location sketch for site LC95-1 showing the northeast end of Lake Zachariah, the brine pond, wetland areas, roads, and creeks. T- tank batteries at the site (see Fig. 2B); B- brine pond, LZ- Lake Zachariah; ZF- Zachariah Fork of Big Sinking Creek. Sketch created from a color infrared air photo. X- locations of water conductivity measurement stations. The scale is approximate.

grass. Two terraced areas occur on the hillslope, one is barren of vegetation and seems to be remnants of a small pit filled with soil. The other is an old tank site with some weathered tank sludge and generally sparse grass. The hillslope along the road is covered by grasses, forbs, small pines, and sumac, a typical disturbance assemblage. Below the lower tank battery is a salt scar. On the upper part of the salt scar, thin soil has eroded away exposing sandstone bedrock. Sediment has accumulated in the lower part of the salt scar just below the sandstone exposure and this zone also remains barren of vegetation. Adjacent areas are heavily wooded with pine and deciduous trees.

Along the west edge of the site, a small stream goes under the road through a culvert and enters a small pool (Fig. 2C). High ground covered with forbs and sumac separates the pool from

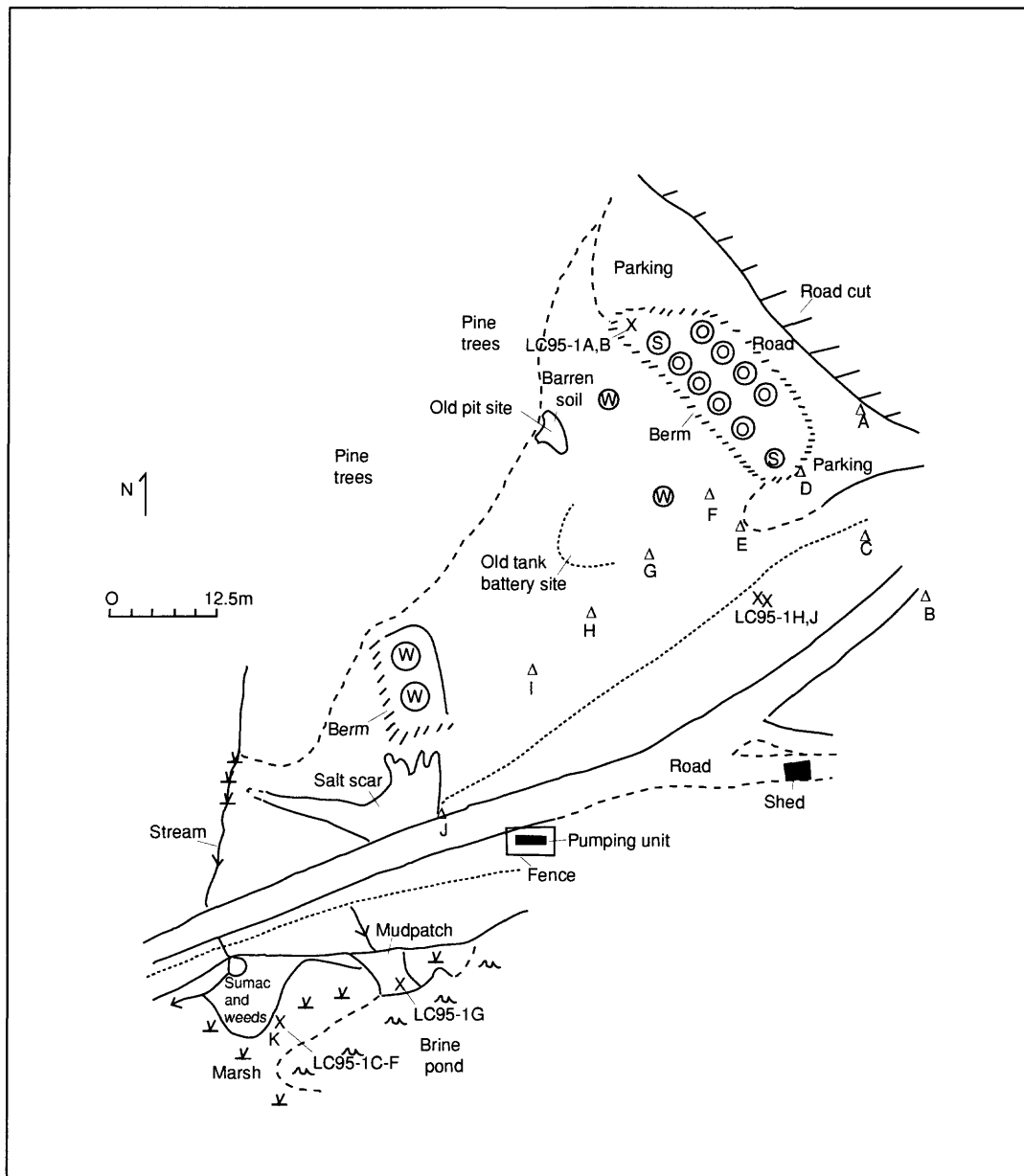


Figure 2B- Detailed map of site LC95-1 created in July 1995 showing cultural and natural features, soil sample sites marked by an "X" (LC95-1A-J), and conductivity survey stations marked by a "Δ" (A-K). O- oil tanks; S- separator tanks; W- produced water storage tanks. Short dash line- breaks in slope. Features along the small stream are mapped in more detail in Fig. 2C.

the wetland. A small wetland has formed along the small stream upvalley from the road where an earthen structure dams the stream. Near the upper end of the wetland is a zone of seeps near the toe of the slope below the tank batteries. The sediment in the seepy zone is colored reddish orange. Farther upvalley above the wetland, a bulldozed area lies adjacent to the stream. The bulldozed area appears to be a reclaimed drillsite. Soil from the bulldozed area was pushed downslope into the stream partly damming it and modifying the channel position. The stream has cut down through this material and has reestablished its gradient.

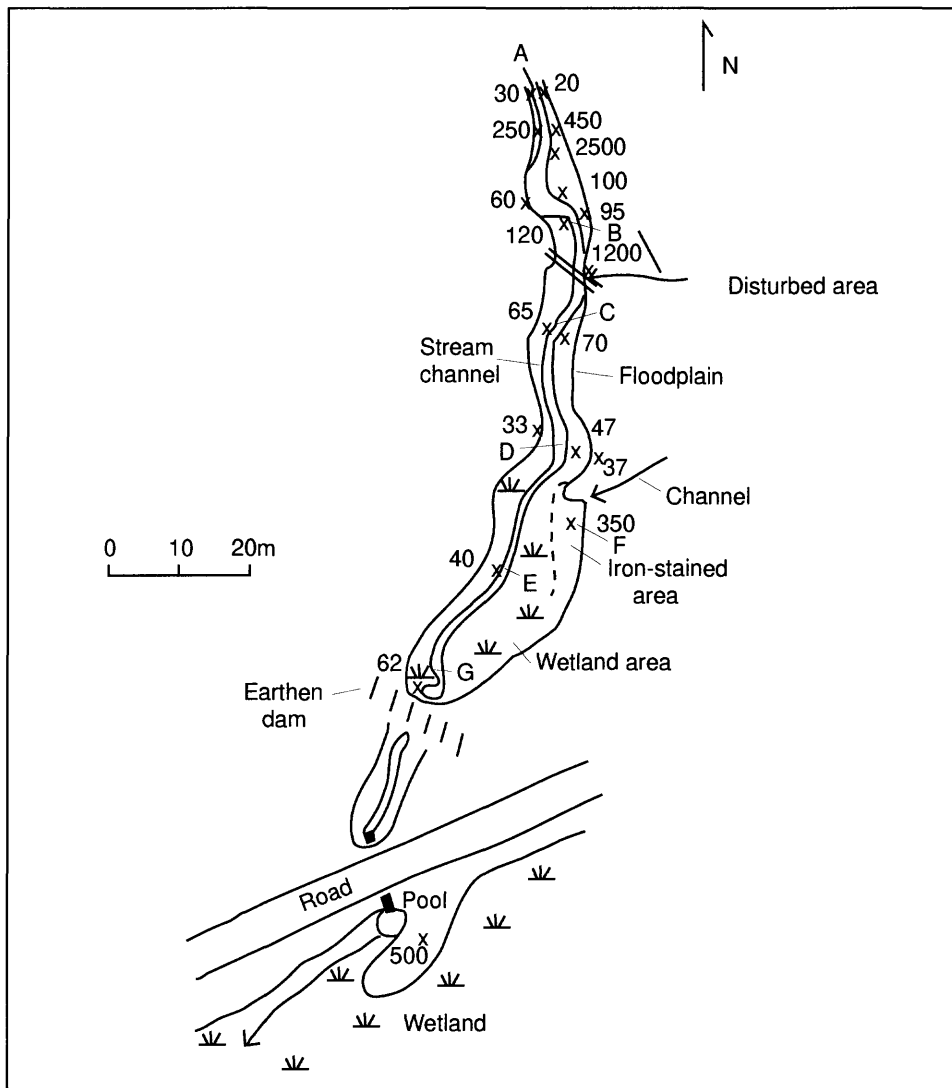


Figure 2C- Detailed map of features along the small stream that flows past the west edge of the tank battery site, mapped in June 1996. Scintillometer readings are shown at stations marked by an "x". Capital letters "A-G" mark survey stations and reference locations for discussion in text.

Radioactivity

Scintillometer readings at Site LC95-1 (Fig. 3A) range from 25 to >10,000 cps (7 to > 1000 $\mu\text{R/hr}$). Background readings were about 25 cps (7 $\mu\text{R/hr}$) on sandy soils and 30 cps (8 $\mu\text{R/hr}$) on clay soils. Highest values were recorded on the soils exposed on the sloped surface between the road and the upper tank battery and a large area here exceeds 1000 cps (174 $\mu\text{R/hr}$). Within this area of elevated readings, two smaller areas measured greater than 5000 cps (590 $\mu\text{R/hr}$) with maximum values >10,000 cps (> 1000 $\mu\text{R/hr}$). The soil exposures with the highest readings were typically discolored (reds and browns) with abundant gray, black, or brown chips (fragments of tank sludge solids). On the slopes near the upper tank battery, lower values generally occur where the layer of shale chips covers the underlying soil.

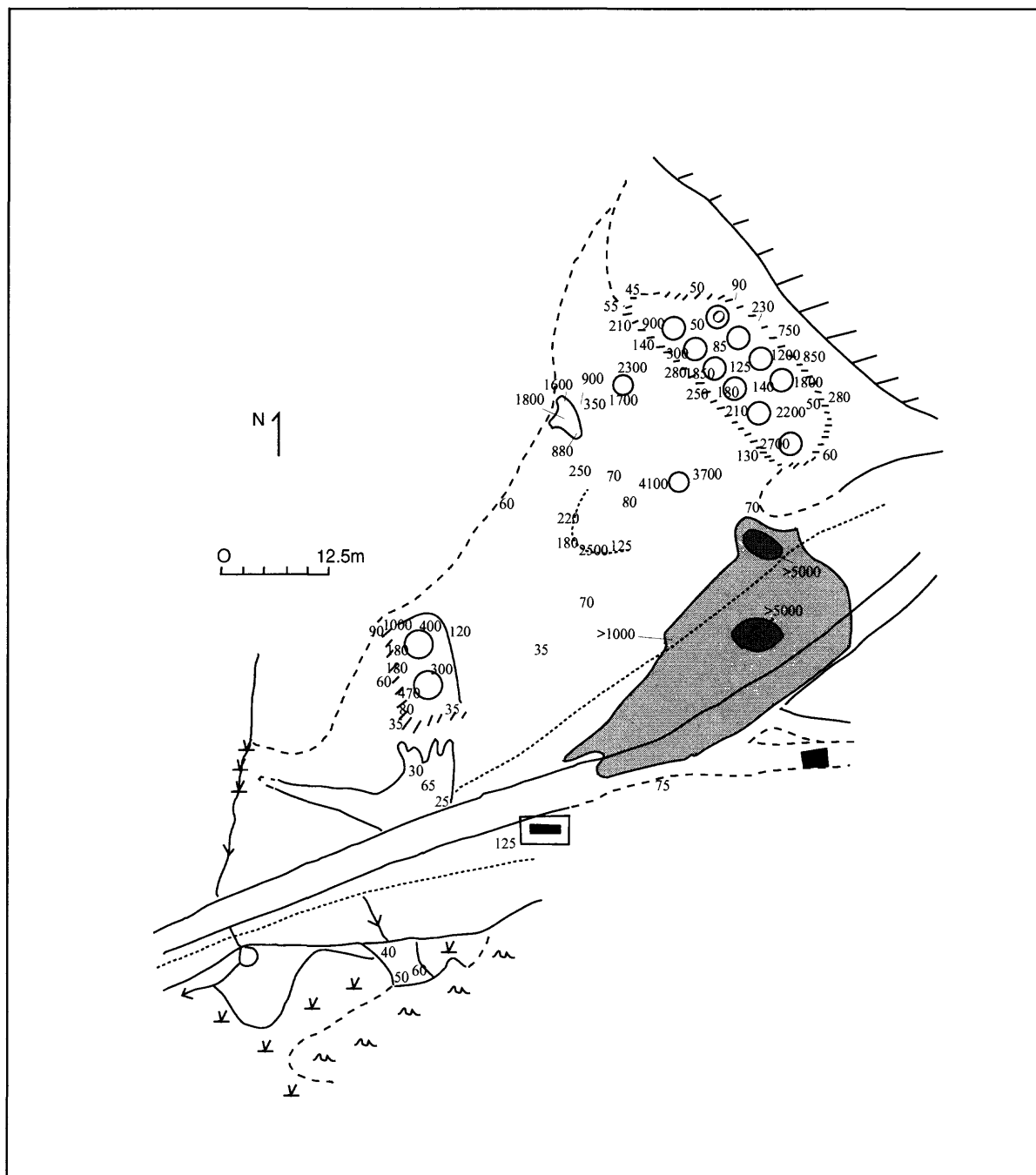
The shale chips that form the berm around the upper tank battery and the surface layer within it have variable radioactivity. Isolated sections of the berm adjacent to the road exceed 1000 cps (174 $\mu\text{R/hr}$). The soil within the berm is as high as 2200 cps (344 $\mu\text{R/hr}$). Highest readings occur where the shale chips seem to be mixed with soil that contains tank sludge solids. Tanks within the upper tank battery range from 50 cps (11 $\mu\text{R/hr}$) at the base to 2700 cps (403 $\mu\text{R/hr}$) at the base of one of the separator tanks. The two tanks on the hillslope between the two tank batteries are highly radioactive with one tank showing a maximum reading of 4100 cps (534 $\mu\text{R/hr}$) at its base and the other a maximum of 2300 cps (357 $\mu\text{R/hr}$).

The lower tank battery is less radioactive. Readings on the berm around the lower tank battery range from 35 to 90 cps (9 to 19 $\mu\text{R/hr}$). The maximum reading on the two water storage tanks is 1000 cps (174 $\mu\text{R/hr}$). Readings in the salt scar below the lower tank battery are 25-30 cps (7-8 $\mu\text{R/hr}$), the local background.

Soils on the hillslope between the two tank batteries are variably radioactive and range from 35-2500 cps (9-380 $\mu\text{R/hr}$). Highest readings are on parts of the two terraced areas (2550 cps (387 $\mu\text{R/hr}$) on the former tank site and 1800 cps (290 $\mu\text{R/hr}$) on the former pit site). The area of high radioactivity on the former tank site is underlain by soil containing chips of tank sludge solids.

At the edge of the wetland, the mud patch gives scintillometer readings of 40-60 cps (10-13 $\mu\text{R/hr}$, water attenuates the gamma activity thus these readings cannot be compared directly to readings on dry soils). Readings as high as 2-3 times background occur in the water-saturated wetland areas adjacent to the mudpatch suggesting that the underlying sediments are radioactive although these readings cannot be compared to readings over nearby dry soils. The low topography covered with sumac and forbs surrounding the small pond (lower left of Fig. 2B) is mostly greater than 100 cps (21 $\mu\text{R/hr}$) with maximum readings of about 500 cps (91 $\mu\text{R/hr}$).

Along the small stream, above areas disturbed by production activities, the sediments on the narrow floodplain adjacent to the



stream channel (site A, Fig. 2C) vary from 20-30 cps (6-8 $\mu\text{R/hr}$). Between sites A and B (Fig. 2C), soil mixed with tank sludge or scale has been pushed downslope from the adjacent bulldozed open area (Fig. 2A). This material has formed a small terrace that has forced the stream channel to the west edge of the floodplain. The disturbed soil on this terrace ranges from 95-2500 cps (20-380 $\mu\text{R/hr}$). Material on the hillslope above the terrace is as much as 1700 cps (280 $\mu\text{R/hr}$). Seeps on the terrace are stained bright orange, probably reflecting oxidation of dissolved ferrous iron in the water. Between sites B and C (Fig. 2C), the stream has cut a channel several tens of centimeters deep into layered deposits of disturbed soil. Dark layers, probably representing concentrations of tank sludge or scale in this disturbed soil, give maximum readings of about 1000 cps (174 $\mu\text{R/hr}$). Soil at a seep in this layered material was also stained bright orange. At and below site C, the scintillometer readings drop gradually to readings less than twice background. Below site D, the floodplain widens, becomes water saturated, and is occupied by wetland plants (*Typhae* and *Salix*). A heavily iron-stained seep occupies the wetland floor along the east edge adjacent to the low end of a narrow gully that intercepts the wetland between sites D and E. The wetland surface is anomalously radioactive wherever the surface is orange colored and radioactivity over the water-saturated surface ranges from 50-350 cps (11-65 $\mu\text{R/hr}$, the maximum radioactivity occurs at site F). *Salix* specimens are limited to the periphery of this seep. At site E, a site isolated from surface water draining the seep around site F, the wetland surface is about 40 cps (10 $\mu\text{R/hr}$). The water-saturated sediment at the small pool just downstream from site G reads about 60 cps (13 $\mu\text{R/hr}$).

In Fig 3B, the cps readings that are shown in Fig. 3A have been converted to $\mu\text{R/hr}$ readings using the formula mentioned above. These values range from 11 to 535 $\mu\text{R/hr}$ on equipment and from 7 to about 1100 $\mu\text{R/hr}$ on soils. Background readings are about 7-8 $\mu\text{R/hr}$. $\mu\text{R/hr}$ readings along the small stream range from 6-380.

Radium

GAD-6 spectrometer readings were taken at 57 stations at this locality (Table 1, Fig. 3C). The readings range from 2 to 413 pCi/g total radium activity. Measurements were not made at the most radioactive sites identified with the scintillometer because the count rate limits of the instrument were exceeded and the data become less reliable when this occurs. However, soil samples from one of these sites were collected and analyzed in the laboratory (LC95-1H,J, Table 2). Sample LC95-1H gave a laboratory-based total radium activity of 1770 pCi/g and sample LC95-1J gave a laboratory-based total radium activity of 3390 pCi/g (average of two lab measurements). Reference GAD-6 spectrometer readings at the site were taken on shale exposed in the roadcut adjacent to the upper tank battery (3 pCi/g total radium activity) and on sandstone outcrop in the salt scar near the lower tank battery (2 pCi/g total radium activity).

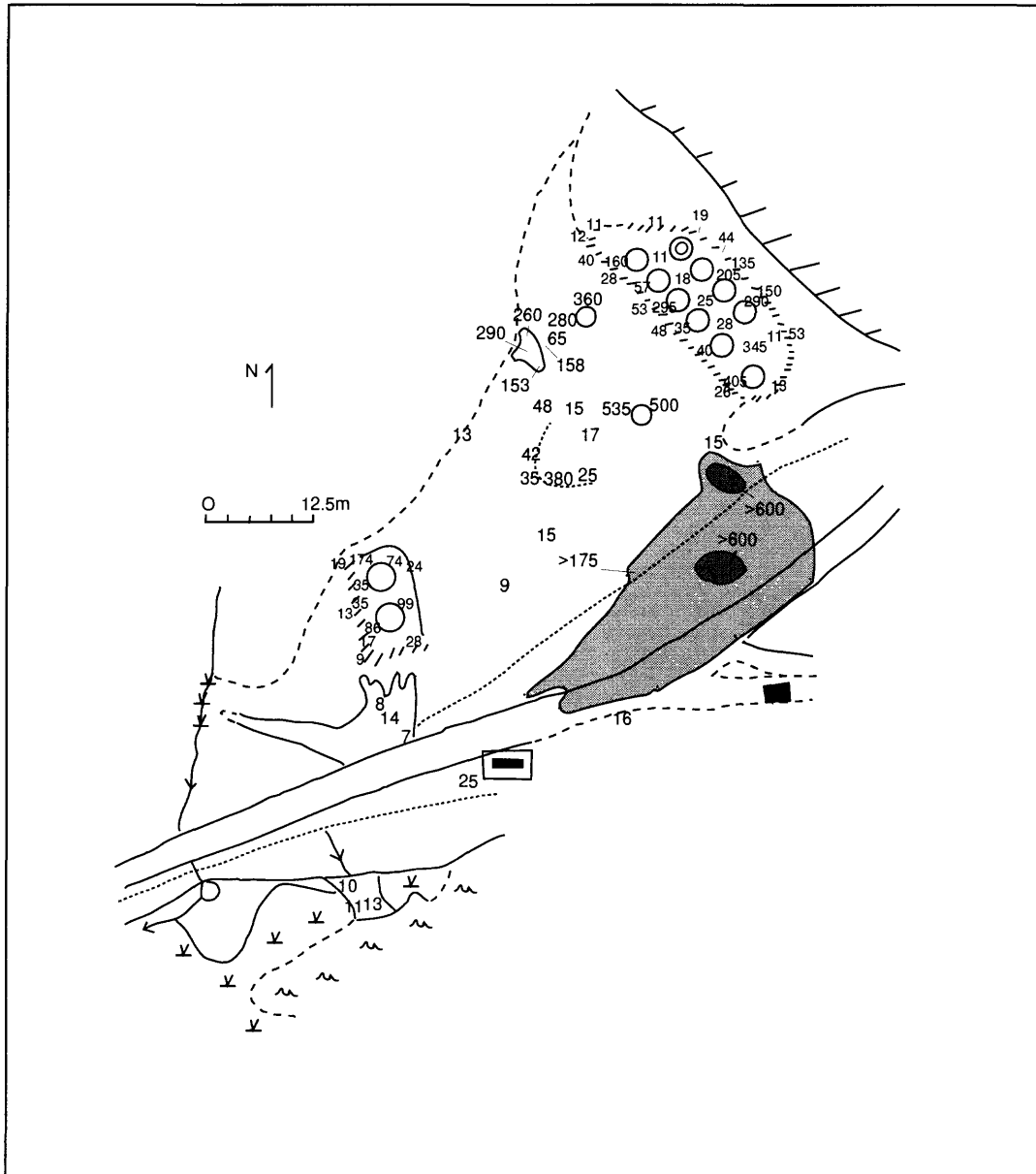


Figure 3B- MicroR/hour readings (converted from scintillometer data) on soils and equipment at site LC95-1. For reference, background readings are 7-8 microR/hour.

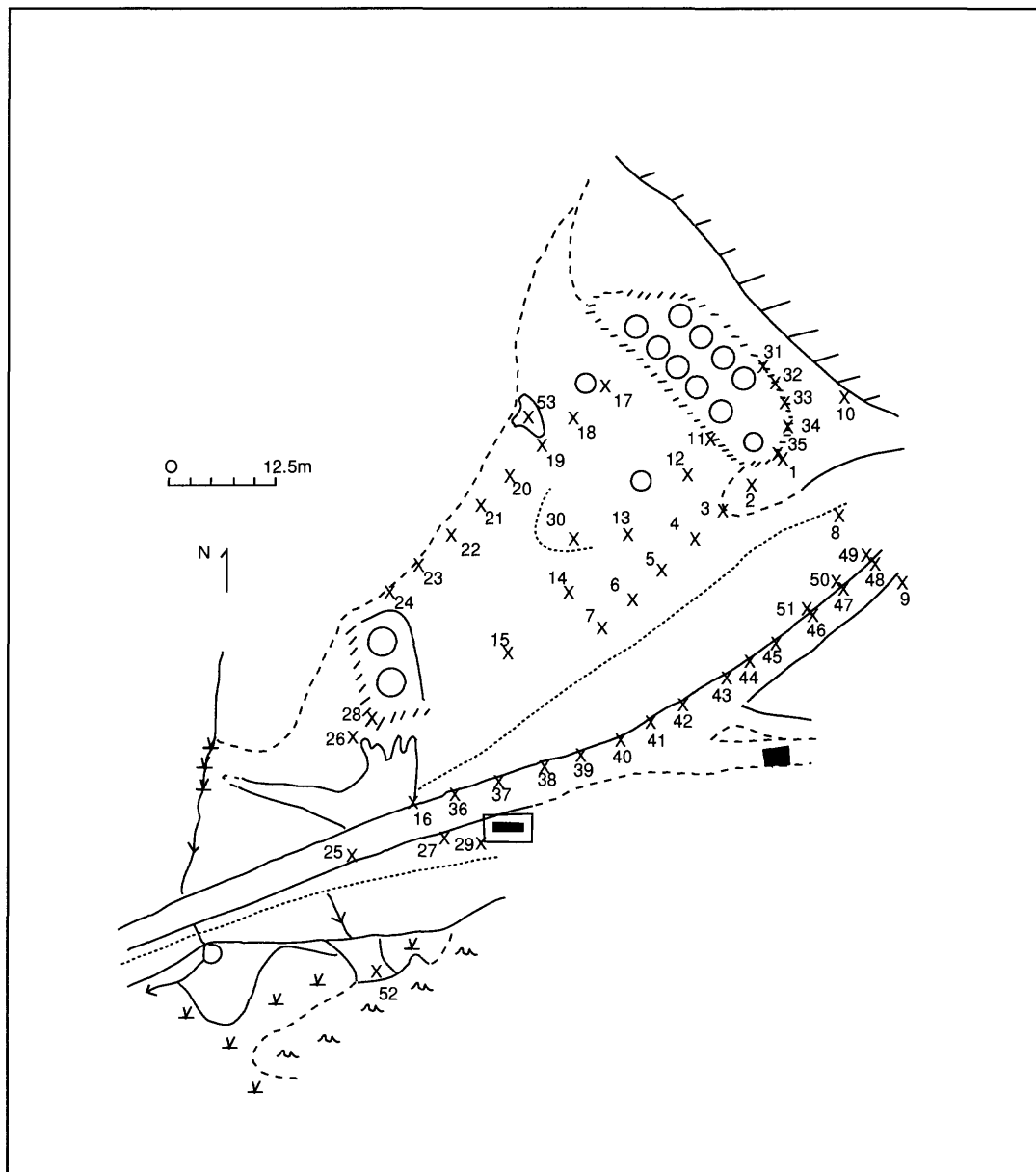


Figure 3C- Numbered GAD-6 spectrometer stations at site LC95-1.
See Table 1 for data keyed to these stations.

Table 1- GAD-6 spectrometer data for Site LC95-1. e- equivalent, meaning that the value reported has been calculated from instrument gamma readings for a radionuclide farther down in the decay chain and that secular equilibrium is assumed. "rep" means that a second instrument reading was taken without moving the instrument; "dup" means that the site was retaken and a second reading made. See Fig. 3C for location of the stations sampled.

Location	eU (ppm)	eTh (ppm)	eRa-226 (pCi/g)	eRa-228 (pCi/g)	Ra-228/Ra-226	Total radium (pCi/g)
1	13.5	16.6	4.50	1.84	0.41	6.34
2	126.2	117.4	42.07	13.04	0.31	55.11
3	20.9	30.5	6.97	3.39	0.49	10.36
4	32.1	49.8	10.70	5.53	0.52	16.23
5	14.5	19.9	4.83	2.21	0.46	7.04
6	21.4	29.3	7.13	3.26	0.46	10.39
7	2.5	6.3	0.83	0.70	0.84	1.53
7 (rep)	2.8	6.7	0.93	0.74	0.80	1.68
8	10.2	19.3	3.40	2.14	0.63	5.54
9	8.2	10.6	2.73	1.18	0.43	3.91
1 (dup)	13.2	17	4.40	1.89	0.43	6.29
10	4.3	9.7	1.43	1.08	0.75	2.51
11	5.7	15.3	1.90	1.70	0.89	3.60
12	6.1	37.9	2.03	4.21	2.07	6.24
13	79.5	65.4	26.50	7.27	0.27	33.77
14	13.4	15.6	4.47	1.73	0.39	6.20
15	5.4	13.1	1.80	1.46	0.81	3.26
16	5.4	5.4	1.80	0.60	0.33	2.40
17	15.6	33	5.20	3.67	0.71	8.87
18	189.1	502	63.03	55.78	0.88	118.81
19	40.6	42	13.53	4.67	0.34	18.20
20	92.7	76	30.90	8.44	0.27	39.34
21	36.4	34	12.13	3.78	0.31	15.91
22	16.1	24	5.37	2.67	0.50	8.03
23	77.2	135	25.73	15.00	0.58	40.73
24	27.5	53	9.17	5.89	0.64	15.06
25	6.7	7	2.23	0.78	0.35	3.01
26	3.3	9.5	1.10	1.06	0.96	2.16
27	5.4	12.6	1.80	1.40	0.78	3.20
28	4.5	10.6	1.50	1.18	0.79	2.68
29	33.1	31.3	11.03	3.48	0.32	14.51
30	721.3	828.1	240.43	92.01	0.38	332.44
31	590	713.5	196.67	79.28	0.40	275.94
32	30.4	139.9	10.13	15.54	1.53	25.68
33	17.2	23.8	5.73	2.64	0.46	8.38
34	11.5	17.8	3.83	1.98	0.52	5.81
35	9.1	13.5	3.03	1.50	0.49	4.53
36	4.7	7.4	1.57	0.82	0.52	2.39
37	7.2	6	2.40	0.67	0.28	3.07
38	6.9	7.6	2.30	0.84	0.37	3.14
39	10.2	8.4	3.40	0.93	0.27	4.33
40	15.3	14.3	5.10	1.59	0.31	6.69
41	18.3	16.1	6.10	1.79	0.29	7.89
42	45.1	26.1	15.03	2.90	0.19	17.93
43	251.9	116	83.97	12.89	0.15	96.86
44	332.6	163.6	110.87	18.18	0.16	129.04
45	63.3	35.2	21.10	3.91	0.19	25.01
46	22.4	18.2	7.47	2.02	0.27	9.49
47	10.5	12.1	3.50	1.34	0.38	4.84
48	8.7	11.6	2.90	1.29	0.44	4.19
49	9.8	15.5	3.27	1.72	0.53	4.99
50	19.5	22	6.50	2.44	0.38	8.94
51	15.6	18.1	5.20	2.01	0.39	7.21
52	33.8	48.5	11.27	5.39	0.48	16.66
53	933	924.4	311.00	102.71	0.33	413.71
Shale bg	4.4	17	1.47	1.89	1.29	3.36
Sandstone bg	3.8	5.7	1.27	0.63	0.50	1.90

Table 2- Laboratory-based radiochemical analyses for samples from selected sites in northern Lee County, Kentucky.

Sample #	Lab	Ra-226 (pCi/g)	Ra-228 (pCi/g)	Ra-228/Ra-226	Total radium (pCi/g)
LC95-1B	1	37.18	16.00	0.43	53.18
LC95-1G	2	45.9	20.9	0.46	66.80
LC95-1H	1	1630.45	138.45	0.08	1768.90
LC95-1J	1	2634.09	174.09	0.07	2808.18
LC95-1J	2	3704.1	258.2	0.07	3962.30
LC95-2A:0-.25m	1	89.32	13.45	0.15	102.77
LC95-2A:0-.25m	2	103.6	11.8	0.11	115.40
LC95-2A:.25-.5m	1	239.59	39.68	0.17	279.27
LC95-2A:.25-.5m	1	198.64	37.32	0.19	235.96
LC95-3A	2	39.5	22.3	0.56	61.80
LC95-6A	2	3.5	3.0	0.86	6.50
LC95-13A	1	45.05	10.86	0.24	55.91
Lab 1- Jim Budahn, U.S. Geological Survey, Denver, CO.					
Lab 2- Thomas Kraemer, U.S. Geological Survey, Reston, VA.					

Pits were dug at several of the most radioactive sites during the 1996 visit. A pit at the hotspot on the hillslope adjacent to the road (site LC95-1H,J, Fig. 2B) showed a sandy surface layer 30-50 cm thick that contained fragments of tank sludge solids. This layer is underlain by a sandy loam which is probably similar to soil at an undisturbed site. A scintillometer profile in this pit suggests that most of the radioactivity is contained in the surface layer. Three pits were dug at and near the edge of the barren soil area at the old pit site on the hillslope between the two tank batteries (Fig. 2B). These pits showed that a layer of oil-saturated sandy soil occurs 7-20 cm below a surface layer of sandy loam within the pit. At the edge of the pit an anomalously radioactive surface layer composed of sandy loam is underlain by an anomalously radioactive clay layer, then less-radioactive sandy loam and weathered bedrock. A pit in the mud patch adjacent to the wetland and brine pond (Fig. 2B) showed a surface layer of gray sandy clay that is underlain by oily clay. The open water of the brine pond near the mudpatch is underlain by several centimeters of organic-rich silty clay with oily clay of unknown thickness below. A pit in the forb- and sumac-covered high ground adjacent to the small pool (Fig. 2B) showed 60 cm of anomalously radioactive grayish-orange sand and 70 centimeters of highly radioactive black, oily clay.

Water quality

Conductivity measurements were made in the water along the small stream adjacent to the site and in the main stream above and below the brine pond. Stream water conductivity at Station A (Fig. 2C) above the bulldozed area along the small stream was 175

$\mu\text{S}/\text{cm}$. This may or may not represent local background as other oil production operations occur upvalley. Water in the iron-stained seep area (station F, Fig. 2C) had a conductivity of 380 $\mu\text{S}/\text{cm}$ whereas conductivities at station G (low end of the small wetland) and in the small pool adjacent to the road berm were 280 and 220 $\mu\text{S}/\text{cm}$, respectively. The conductivity measurement in the Zachariah fork of Big Sinking Creek above the brine pond was 310 $\mu\text{S}/\text{cm}$ whereas the conductivity reading in the stream channel adjacent to the downstream end of the levee below the brine pond was 420 $\mu\text{S}/\text{cm}$ (Fig. 2A). Both of these streams show increases in conductivity of about 35-45 percent as they flow past the tank battery and the associated brine pond. The bottom of the Zachariah fork channel adjacent to the brine pond is iron-stained. Small fish were observed in the stream channel above and adjacent to the brine pond. Conductivity of the water in the brine pond was 15,600 $\mu\text{S}/\text{cm}$ (1996 measurement).

Water chemistry

A single water sample (LC95-1W, Table 5) was collected from the surface of the wetland away from the pond (same location as auger samples LC95-1C-1F, Fig. 2B). This sample had a field conductivity of 620 $\mu\text{S}/\text{cm}$, higher than the adjacent streams, but lower than the brine pond, and a radium-226 activity of 4.7 ± 0.4 pCi/L.

Soil conductivity

Soil conductivity measurements were made at 11 stations at this site (Fig. 2B, A-K, Table 3). Readings at 6 sites (B,F,G,H,J,K) were influenced in whole or in part by buried pipe. Readings at the site inferred to be least affected by brine movement (A, Fig. 2B) showed 6 m conductivities of about 36 mS/m and 3 m conductivities of about 25 mS/m. These values probably reflect conductivities in the shale exposed in the roadcut. Values at stations close to the southeast end of the upper tank battery (C,D,E, Fig. 2B) were generally slightly lower than these readings. These values likely reflect the conductivity in the shale chip fill and underlying sandy tank sludge and scale, sandy loam soil, and sandstone bedrock. The 6 m sounding data for stations H and I (underlain by sandstone) were nearly twice that of station A whereas the 3 m sounding data for station I was lower than that of station A. Slightly saline bedrock may be present in deeper horizons below stations H and I. The 3 m sounding data for station K in the wetland were the highest of the reliable readings observed at the site. These data suggest that, in spite of evidence that brines have moved through these soils and that brine-derived solids have often been discarded on the soil surface, the soil and permeable bedrock pore waters are generally not very conductive. High rainfall has likely flushed most salts from the upper 6 m. Waters in the brine pond and the wetland appear to be far more saline than those anywhere on the hillslope.

Table 3- EM-31 conductivity readings for Site LC95-1. All readings in mS/m. See Fig. 2B for station locations.

Location	Vertical dipole	Perpendicular	Horizontal dipole	Perpendicular
A	37	36	25	25
B*	16	21	8	14
C	22	24	15	17
D	34	32	28	30
E	27	24	17	14
F*	105	32	42	20
G*	89	20	29	12
H	62	60	19*	24*
I	55	62	19	21
J*	33	negative	35	280
K	115*	80*	75	80

*- data for entire location or dipole orientation not valid, cultural effects.

Table 4- Trace element data for soil samples from selected sites in Lee County, Kentucky.

Sample	Fe (%)	Cu (ppm)	Pb (ppm)	Zn (ppm)	Cd (ppm)	Zr (ppm)	Sr (ppm)	Ba (ppm)	Br (ppm)	I (ppm)
LC95-1A	5	<20	40	45	<1	140	335	2900	5,10	
LC95-1B	4.3	20	40	95	<1	175	665	8400	1,5	
LC95-1C	2.4	<20	<40	<40	<1	265	350	2500	2,10	
LC95-1D	2.5	<20	<40	60	<1	250	630	3820	5,10	
LC95-1E	2.4	<20	40	40	<1	285	775	5260		
LC95-1F	2.3	35	<40	50	<1	270	200	1240		5,10
LC95-1G	5.1	<20	<40	90	<1	290	675	6110	10,50	10,50
LC95-1H	7.1	165	200	100	<1	<10	>20000	>30000		
LC95-1J	4.4	195	245	30	<1	<10	48900	>30000		10,20
LC95-2A1	2	30	<40	25	1	240	2635	12070		
LC95-2A2	2.9	50	40	<40	<1	180	5355	>20000		#
LC95-2B1	2.7	<20	<40	80	<1	295	190	1100		
LC95-2B2	2.7	25	<40	100	<1	275	455	3440	1,5	
LC95-3A	3	<20	<40	70	<1	170	480	8300	10,50	10,20
LC95-6B	1.7	<20	<40	40	<1	475	100	325		
LC95-6C	1.7	<20	<40	60	<1	475	100	415		5,10
LC95-6D	2.4	<20	<40	60	<1	480	100	385		
LC95-13A	1.9	<20	<40	45	<1	250	570	5900		

#- interferences from barium. A range of values is reported for bromine and iodine.

Soil geochemistry

Several soil samples were taken from this site and analyzed for trace elements (LC95-1A-J, Table 4). Samples LC95-1A and 1B were taken from the sump hole at the northwest end of the upper tank battery (Fig. 2B). Sample 1A contained abundant dried algal matter in addition to the sump bottom sediment. Samples 1C-F represent four 0.25 m sample intervals from a 1 m auger hole in the wetland. Sample 1G is a surface grab sample from the mudpatch adjacent to the wetland. Samples 1H and 1J are from the hotspot on the hillslope next to the road.

Samples 1H and 1J contain high concentrations of barium and strontium and less than detectable (<10 ppm) concentrations of zirconium, a common, highly insoluble component of most soils in the area (note values of 140-180 ppm in all the other samples). These data suggest that most of the material in these samples is composed of sandy tank sludge solids derived from the adjacent tank battery site. Barite probably forms a substantial part of these two samples. These two samples also contain the highest concentrations of radium, copper, and lead of samples collected in this study.

Other samples collected at this site also have unusually high concentrations of barium (1240-8400 ppm) and strontium (200-775 ppm) compared to silty and sandy wetland samples at site LC95-6 (Table 4). These samples contain copper and lead at levels generally at or below the detection limit. Detectable bromine occurs in the sump hole samples, in the upper part of the wetland augerhole, and in the mudpatch samples. Bromine may be sorbed on organic matter which is present in each of these samples. Detectable iodine occurs in the lower part of the augerhole, the mudpatch, and one of the hotspot samples.

Four samples were analyzed radiochemically in the laboratory for radium-226 and radium-228 (Table 2). A sample of the sediment from the sump pit at the southwest end of the upper tank battery (LC95-1B, Table 2, Fig. 2B) gave a laboratory-based total radium analysis of 53 pCi/g. A sample from the mudpatch (LC95-1G, Table 2, Fig. 2B) had a laboratory-based total radium analysis of 67 pCi/g. As noted above, samples from the surface layer in the hotspot (LC95-1H, 1J) had laboratory-based total radium analyses of 1770 and 3390 pCi/g.

LC95-2

This site lies on a hillslope and the adjacent floodplain on the west side of Townshend Fork of Big Sinking Creek just upstream from where a dirt road crosses the drainage. Lake Zachariah is a few tens of meters downstream from the road crossing (Fig. 1B, Fig. 4). The site includes a tank battery on the hillslope, a large, partly-filled-in, vegetated brine pond on the stream floodplain, and a smaller brine pit on the stream floodplain.

Table 5- Water chemistry data for two samples from Sites LC95-1 and LC95-3. Conductivity measurements in microS/cm.

	Samples	
	LC95-1W	LC95-3W
<u>Parameters</u>		
Field temp (°C)	27	28.5
Field pH	7.3	7.2
Lab pH	6.8	7.3
Field conductivity	620	205
Lab conductivity	500	180
<u>Cations</u>		
Ca (ppm)	42	14
K (ppm)	0.5	0.78
Mg (ppm)	9.1	3.5
Na (ppm)	33	16
Sr (ppm)	2.1	0.8
Ra-226 (pCi/L)	4.7±0.4	0.05±0.01
<u>Anions</u>		
HCO ₃ (ppm)	130	25
CO ₃ (ppm)	0	0
Cl (ppm)	82	33
SO ₄ (ppm)	3.2	8.5
TDS (ppm)	302	102

The tank battery includes 4 oil storage tanks which were at background (25 cps, 7 μ R/hr) and a brine storage tank which gave a reading of 200 cps (39 μ R/hr). A separator tank farther up the hill was about 200-225 cps (39-43 μ R/hr). The brine pond site is dry at its south end, but is wet and supports lush wetland vegetation in its north end (Fig. 4). The surface sediment in this pond is sandy. The surface radioactivity in the south end of the brine pit was less than 100 cps (21 μ R/hr), however maximum readings over the water-saturated north end were 700 cps (125 μ R/hr). An auger hole in the dry, south end of the brine pond showed 50 cm of limonite-stained clayey sand and 50 cm of gray clayey sand. An auger hole in the north end of the pond (Fig. 4) intersected 25 cm of limonite-stained sand that is underlain by 75 cm of oil-saturated clayey sand. The oil layer may have created a perched water table allowing the wetland to form. The wetland environment, in turn, may have created a favorable zone for radium to accumulate. The upper two 25 cm intervals in this auger hole were analyzed for radium (LC95-2A, Table 2) and trace elements (LC95-2A, Table 4).

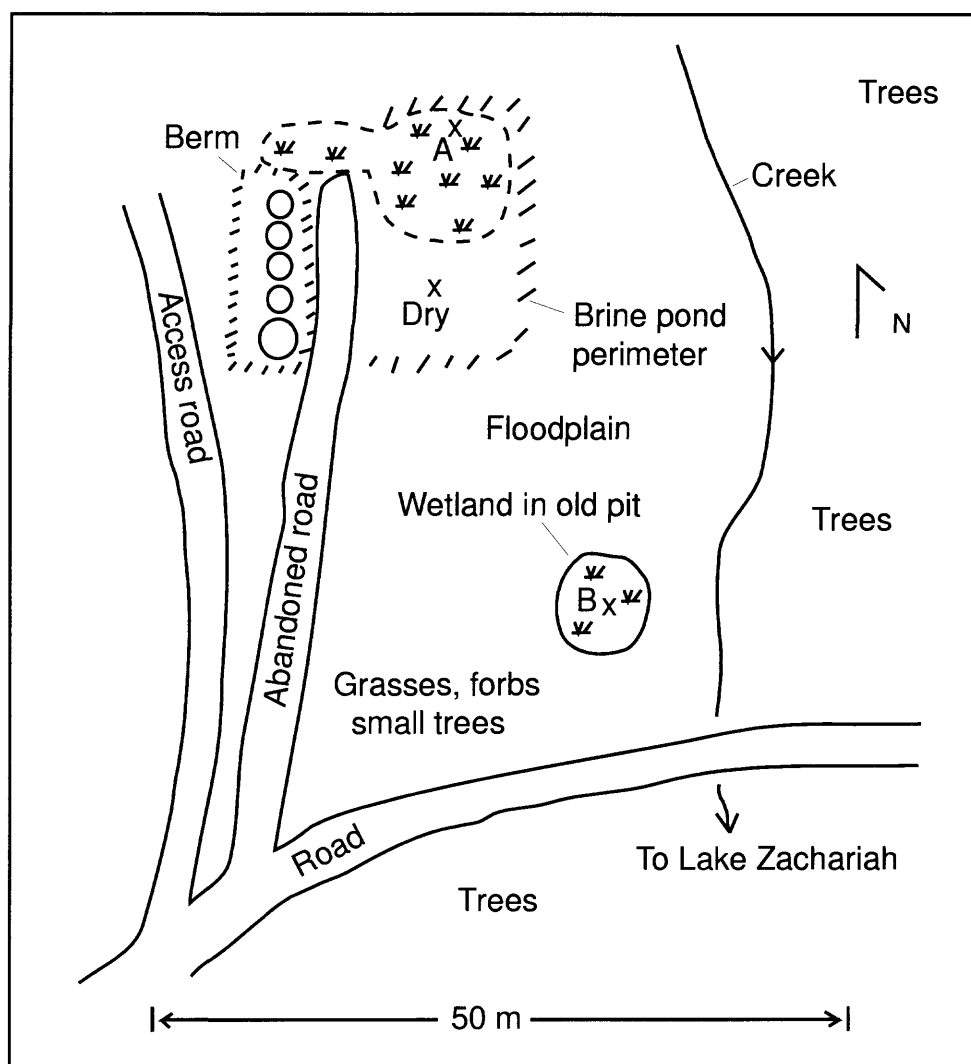


Figure 4- Sketch map of features at site LC95-2. X- locations of augerholes. Samples were taken from selected intervals in holes labeled "A" and "B". Not to scale. Distance noted was determined by measuring tape along the road. North is approximately located.

Laboratory-based total radium analyses in this augerhole ranged from about 100-280 pCi/g. Barium and strontium concentrations were high in these two samples suggesting that barite is present. Copper, lead, and zinc were detected in one or both of these samples. Cadmium was barely detected (at 1 ppm) in the uppermost 25 cm interval.

The pit lies to the south adjacent to the road. The surface is damp, muddy, and is occupied by cattails, pickerelweed, and *Juncus*. The surface sediment was 40-50 cps (10-11 $\mu\text{R/hr}$). An auger hole in the middle of this feature intersected 85 cm of mud with abundant organic matter and light oil and 15 cm of hematite-stained clayey sand with no hydrocarbons. The upper 50 cm

contained anomalous concentrations of strontium and barium, elevated zinc (80-100 ppm), and copper and lead concentrations near or below the detection limit. Trace amounts of bromine were detected in the 25-50 cm interval of this augerhole.

LC95-3

This site includes three areas with above background radioactivity near Lake Zachariah dam (Fig. 1B). The dam is earth filled and is capped by a concrete wall and a gravel road. At the south end of the dam is a concrete spillway that directs water into a channel cut into shale bedrock. This channel returns water to the natural stream channel downstream from the dam.

Radioactive soil occurs below two brine discharge pipes adjacent to the north end of the dam. At one of the sites, a white PVC pipe protrudes from the ground near the base of the berm of the road a few meters above the level of the lake. The end of the pipe is a few meters from the edge of the lake. Flow from the pipe has partly eroded the soil on the slope and has deposited sediment at the lake's edge. This sediment measured 300 cps (57 $\mu\text{R/hr}$). The laboratory-based total radium activity in a sample of this radioactive sediment was 62 pCi/g (LC95-3A, Table 2). At a second locality about 10 meters away from the first, a black PVC pipe protrudes from the berm of the dam. Soil between this pipe and the lake edge reads about 100 cps (21 $\mu\text{R/hr}$).

The third area occurs in a marsh below the toe of the dam upstream from where the channeled surface flow returns to the natural stream channel. The water supplied to this wetland is inferred to be seepage from the dam. Scintillometer readings on the water-saturated surface of the wetland were about 200 cps (39 $\mu\text{R/hr}$).

Water in the spillway was sampled in July of 1995 (Table 5) and showed a field conductivity of 205 $\mu\text{S/cm}$. This sample also had a radium-226 activity of 0.05 ± 0.01 pCi/L. Conductivity was remeasured in the June of 1996 at 300 $\mu\text{S/cm}$. Small fish were observed in spillway pools in June of 1996.

LC95-4

Site LC95-4 is just upstream from the confluence of Big Sinking Creek and a small unnamed tributary about 0.8 km from the Lake Zachariah dam on the north side of the creek (Fig. 1B). It includes two oil tanks, a brine tank, and a separator. A filled-in brine pond is at the site. The separator read 60 cps (13 $\mu\text{R/hr}$, about twice background). The other tanks, an old flow line leading to the brine pond, and the surface soils over the brine pond site were at background.

LC95-5

This site is located at the confluence of Coal Bank Hollow and Big Sinking Creek (Fig. 1B). It includes a brine storage tank, an old brine pit, and an overflow pit. The base of the brine storage tank read 700 cps (125 $\mu\text{R/hr}$). The surface of the old brine pit was less than background.

LC95-6

Site description

This site consists of a tank battery on the crest of Schumaker Ridge southeast of the Big Sinking Creek oilfield (Fig. 1B, Fig. 5). A mostly revegetated salt scar surrounded by pine trees extends downslope to the southwest towards a wetland that lies along a flat-bottomed valley. The trunks of several salt-killed trees occur in the wetland for a few hundred meters downvalley. This site was last operational during 1984-1985 (Ferris Sexton, Division of Water, Hazard, Kentucky, oral commun. 1995).

We mapped the site and conducted a GAD-6 spectrometer survey and a conductivity survey at stations along a profile downslope from the berm of the tank battery across the salt scar to a dirt road (Fig. 6, Fig. 7). An additional gamma-spectrometer and conductivity site was established in the wetland downslope from the end of the continuous profile. A 1-m hole was augered at the wetland survey site and sampled on 0.25 m intervals. The uppermost interval was analyzed for radium activity (LC95-6A, Table 2) and the lower three intervals were analyzed for trace elements (LC95-6B-D, Table 4).

The hillslope is only slightly eroded and an area of barren soil persists on the steepest part of the hillslope. At the low end of the old salt scar, an additional area of barren soil persists. Rills have formed on the upper part of this lower barren surface and they coalesce into a single narrow channel near the midpoint of the scar. Just downslope from this larger scar is an area of sediment accumulation adjacent to the channel which is also barren of vegetation.

Surface flow from this channel moves downslope along and across the road and into another channel which feeds into another salt scar. Gravel was placed on the surface of the upper part of this salt scar apparently to accommodate parking when the site was active. Surface flow from this lower salt scar enters into the wetland at several points.

Radioactivity and radium

The storage tanks were empty and read at background (25-30 cps, 7-8 $\mu\text{R/hr}$). The revegetated salt scar, the small active salt scars, and the wetland were all at to slightly above background (25-40 cps, 7-10 $\mu\text{R/hr}$). The GAD-6 spectrometer profile (Table 6, Fig. 6) shows background total radium activity (2.13 pCi/g) at the tank battery berm and elevated values in the upper salt scar and the forbs below the upper salt scar (3.38-4.06 pCi/g). The total radium activity in the lower salt scar drops to values above the local background, but below those in the upper salt scar (2.62-2.77 pCi/g). Highest GAD-6 spectrometer total radium activity occurs in the wetland site (4.38 pCi/g). The upper 25 cm interval in the augerhole at this same site had a laboratory-based total radium activity of 6.50 pCi/g. The GAD-6 spectrometer readings at the wetland station may have been suppressed by water saturation. The Ra-228/Ra-226 values (Table 6, Fig. 6) are generally highest in the upper part of the GAD-6 profile and drop

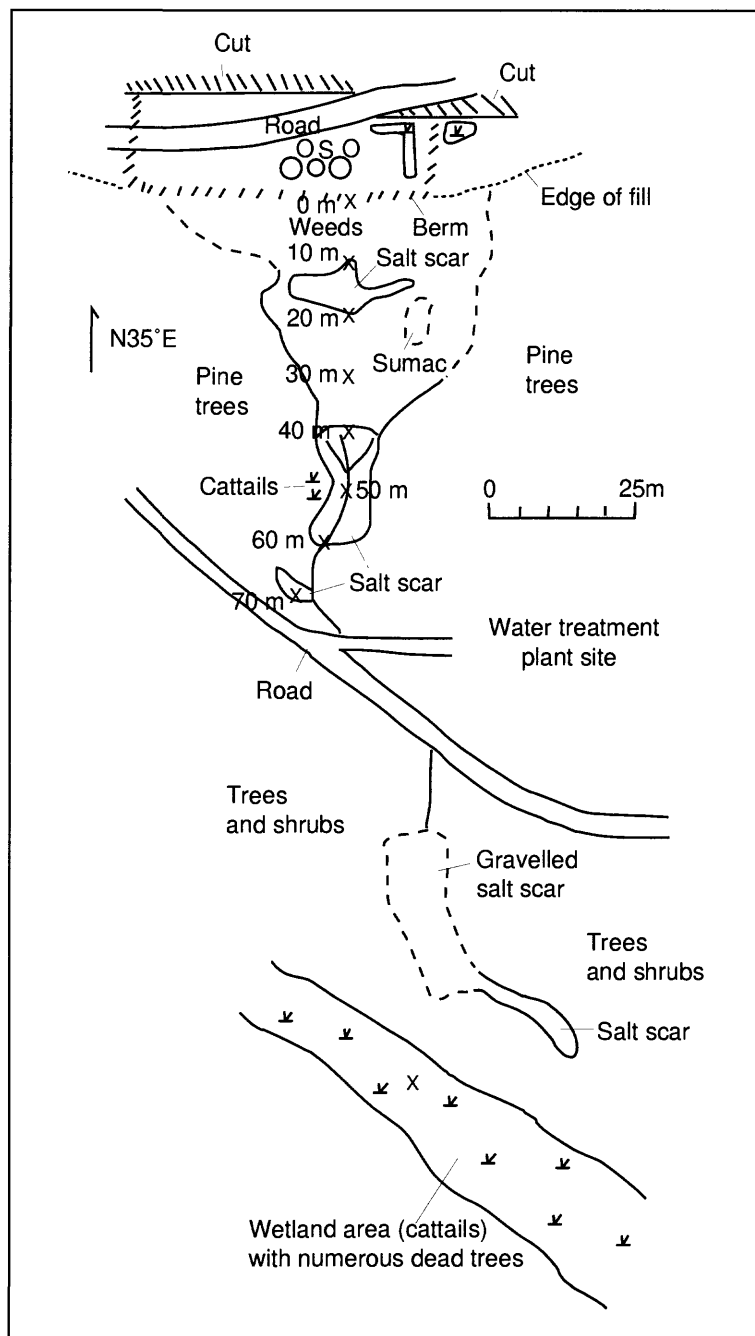


Figure 5- Detailed map of site LC95-6 showing cultural and natural features. The site slopes from the top of the figure down to the wetland. X- profile sites used in Figs. 6 and 7.

irregularly downslope. The ratios for the GAD-6 spectrometer reading and the laboratory-based radiochemical analysis of the surface sample in the wetland are essentially identical (0.86 and 0.88, respectively).

Table 6- GAD-6 spectrometer data for Site LC95-6. e- equivalent, meaning that the value reported has been calculated from instrument gamma readings for a radionuclide farther down in the decay chain and that secular equilibrium is assumed.

Site location	eU (ppm)	eTh (ppm)	eRa-226 (pCi/g)	eRa-228 (pCi/g)	Ra-228/Ra-226	Total radium (pCi/g)
0m	2.30	12.3	0.8	1.4	1.78	2.13
10m	4.30	17.5	1.4	1.9	1.36	3.38
20m	3.90	21.4	1.3	2.4	1.83	3.68
30m	4.80	22.1	1.6	2.5	1.53	4.06
40m	3.90	13.2	1.3	1.5	1.13	2.77
50m	4.20	10.8	1.4	1.2	0.86	2.60
60m	3.40	12.9	1.1	1.4	1.26	2.57
70m	3.60	12.8	1.2	1.4	1.19	2.62
Wetland	7.00	18.4	2.3	2.0	0.88	4.38

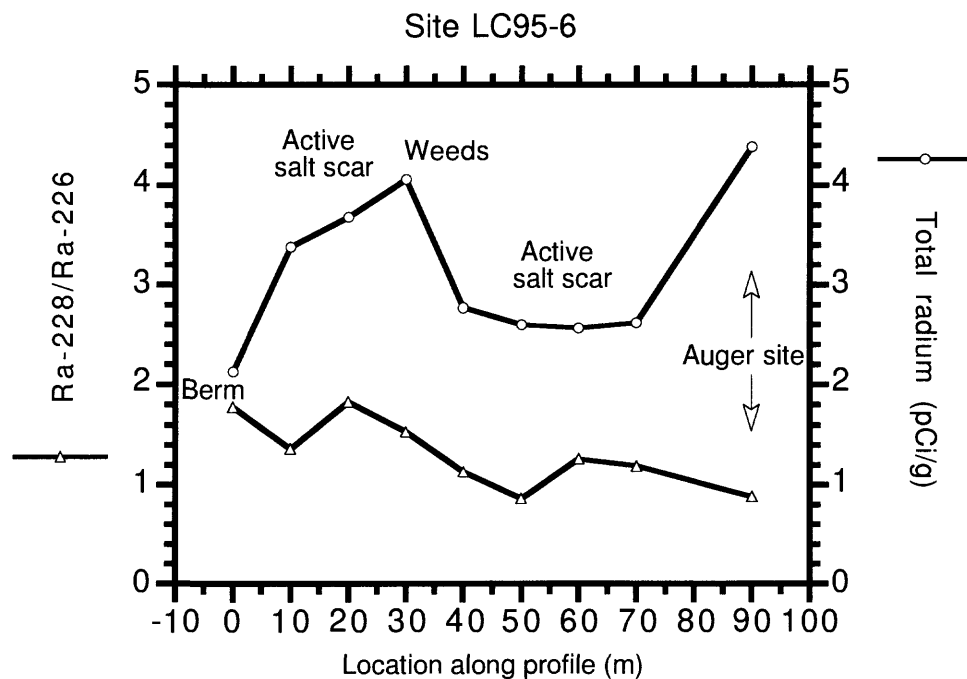


Figure 6- Profiles of total radium and the Ra-228/Ra-226 derived from GAD-6 spectrometer readings along stations down the axis of the salt scar at Site LC95-6 (Fig. 5). Station shown at 90 m is the auger site in the wetland.

Soil conductivity

The soil conductivity profile (Fig. 7, Table 7) shows background values for the berm site and elevated values associated with the two active salt scars (peak values of about 110 mS/m at 6 m in the upper salt scar and about 80 mS/m at 6 m in the lower

salt scar). In all cases, the 3 m readings are less than the 6 m readings. The values in the wetland are too divergent to be reliable.

Soil geochemistry

The wetland auger samples contain less-than-detectable amounts of copper, lead, and cadmium and modest concentrations of zinc (LC95-6B-D, Table 4). Zirconium, strontium, and barium seem normal for soils in this area. Trace amounts of iodine were detected in one sample interval.

Table 7- EM-31 conductivity readings for Site LC95-6. All readings in mS/m. See Fig. 5 for station locations.

Grid point (m)	Vertical dipole	Perpendicular	Horizontal dipole	Perpendicular
0	45	50	28*	35*
10	112	102	85	73
20	88	88	62	60
30	78	82	48	51
40	70	70	51	51
50	77	81	51	56
60	60	57	48	43
70	63	60	48*	39*
Wetland*	81	49	65	54
*- data for entire location or dipole orientation not valid, cultural effects.				

LC95-7

Site LC95-7 includes an operating tank battery just downstream from a small brine storage reservoir in the upper part of the Cave Fork drainage (Fig. 1B). The bermed tank battery is on a hillslope adjacent to the stream. It includes a separator, 7 upright oil storage tanks, and 2 horizontal oil storage tanks. An older separator and some wooden storage tanks are nearby. A *Typhae*-dominated wetland occurs on the stream floodplain below the tank battery. Part of the wetland surface is devoid of vegetation. A brine pit filled with soil also occurs on the floodplain. The surface of the pit is seeping oil at several spots. Local background scintillometer readings are about 30 cps (8 μ R/hr).

The oil storage tanks are at background and the separator tank is about twice background. The salt-scarred area in the wetland is about 70 cps (15 μ R/hr). A GAD-6 spectrometer reading on the toe of the salt scar in the middle of the wetland gave a total radium activity of 7.4 pCi/g.

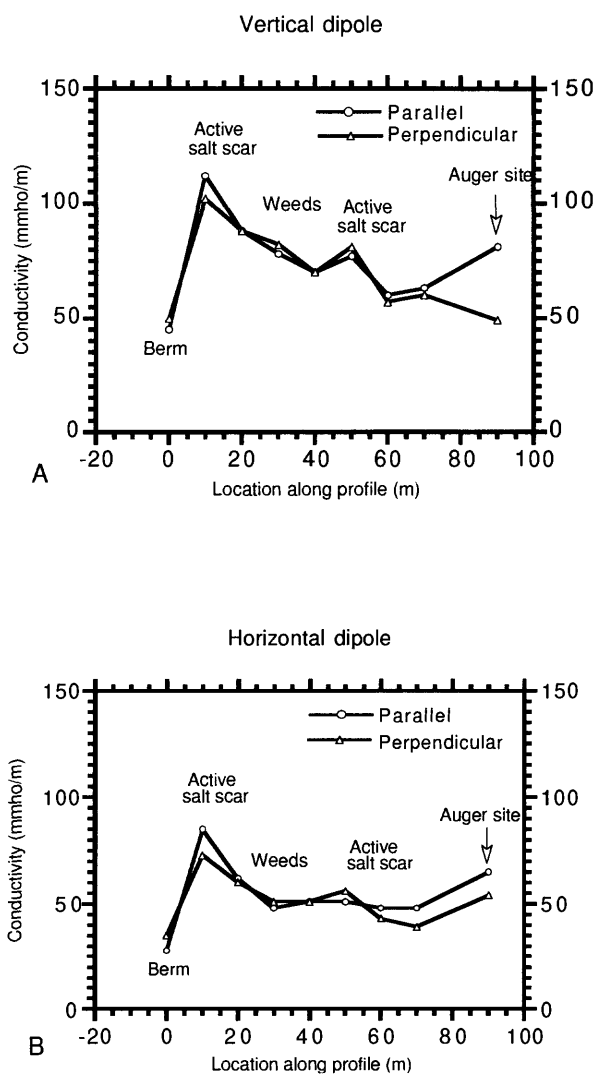


Figure 7- Profiles of conductivity readings along stations down the axis of the salt scar at site LC95-6 (Fig. 5). Station shown at 90 m is the auger site in the wetland.

- A- Vertical dipole readings (6 m).
 B- Horizontal dipole readings (3 m).

LC95-8

This site is located about 0.7 km downstream from the Caves Fork brine storage reservoir, just upstream from the confluence with a small, unnamed tributary (Fig. 1B). A tank battery with 5 oil tanks and one separator are present. A brine pit is present on the floodplain of the creek. The separator read about 45 cps (11 mR/hr). The oil tanks, the pit, and adjacent areas were at background or below. A nearby green water storage tank read 450 cps (83 mR/hr).

LC95-9

This site includes a tank battery and a nearby reclaimed brine pit on a stream terrace above the floodplain of Caves Fork (Fig. 1B). The battery includes 5 oil tanks and a water tank. The water tank gave a 800 cps (140 μ R/hr) maximum reading. The brine pit has been covered with a mound of soil with a moat around it. Part of the mound is devoid of vegetation. Background is about 30 cps (8 μ R/hr). The mound reads 40-70 cps (11-15 μ R/hr). Oil-soaked soil (tank sludge?) near the water tank read 300 cps (57 μ R/hr).

Two water tanks on the hillslope above this tank battery read about twice background and sludge-stained soil near one of the tanks read 6 times background.

LC95-10

This site is on the northwest side of Caves Fork about 200 m upstream from the confluence with Hog Gap Hollow (Fig. 1B). This is an old water treatment site with two old tanks, several old sheds, and a reclaimed brine pit. The tanks are slightly above background. The outlet pipe to one tank is about 90 cps (19 μ R/hr). A 1.3-1.5 m high mound of soil covers the brine pit. Oil-soaked soil on the surface of the mound reads as much as 60 cps (13 mR/hr).

LC95-11

A water treatment plant is located on the hillslope south of Caves Fork just downstream from the confluence of Caves Fork and Hog Gap Hollow (Fig. 1B). A small brine storage reservoir is located on a small tributary uphill from the plant and two tank batteries are located on the site. The tank battery located high on the hillslope contains three water tanks and a separator. The water tanks yielded maximum readings of 480, 750, and 1150 cps (90, 130, 200 μ R/hr), respectively. The separator read 45 cps (11 μ R/hr). Soil in and near a brine pit near the upper tank battery was above background. Exposed mud in a small cattail wetland area at the spillway to the reservoir was at background. The lower tank battery includes three tanks; a white water tank which measured 35 cps (9 μ R/hr) and two brown water tanks that measured 900 and 1050 cps (160 and 180 μ R/hr), respectively. Soil downslope from the lower tank battery was as much as 90 cps (20 μ R/hr). A mudflat area along the stream below the brine storage reservoir measured 35 cps (9 μ R/hr).

LC95-12

This site is located along the north side of Bald Rock Fork about 100-150 m upstream from its confluence with Big Sinking Creek (Fig. 1B). A large tank battery is located at the site with 4 water tanks and 8 oil tanks. The water tanks yielded 300, 680, 200, and 300 cps (57, 120, 40, and 57 $\mu\text{R/hr}$), respectively. Tank sludge solids on the ground near one of the tanks read 900 cps (160 $\mu\text{R/hr}$).

LC95-13

This site consists of an area of radioactive soil in a ditch along the west side of the dirt road just to the north of site LC95-1 (Fig. 1B). The radioactive zone is about 50 m long and is confined largely to the floor of the ditch itself. The soil in the ditch ranges from background (25-30 cps, 7-8 $\mu\text{R/hr}$) at the margins of the radioactive area to 1200 cps (200 $\mu\text{R/hr}$) in the most radioactive area. An old wellsite lies upslope from the ditch, but equipment and soils at the site measured near background. A patch of shaly soil devoid of vegetation occurs near the north end of the radioactive zone. A piece of pipe protrudes from the undergrowth along the east side of the road just south of the radioactive zone. The pipe measured 300 cps (55 $\mu\text{R/hr}$). A sample of soil from the ditch about 3-4 m south of the barren soil patch contained 56 pCi/g in a laboratory-based analysis of total radium (Table 2) and above background concentrations of barium and strontium (Table 4). Other trace elements were present at near background concentrations.

DISCUSSION AND CONCLUSIONS

Salt scarring and erosion

Minor salt scarring and limited soil erosion occur at some oil production sites in northern Lee County. Where salt scars have formed in the recent past (1984-1985 at Site LC95-6), disturbed-site vegetation (grasses, forbs, and sumac at site LC95-6) has regrown rapidly across most of the site leaving only two relatively small areas barren of vegetation. Persistent shallow salty soil, suggested by elevated soil conductivity readings at these two small areas, is the likely cause. Shallow rills have formed on the surface of these salt scars and some soil has been transported downslope. At site LC95-1, a small salt scar has formed at the base of the hill below the lower tank battery. The upper part of the salt scar closest to the lower tank battery has exposed sandstone bedrock and it is presumed that the lack of soil has prevented regrowth of vegetation. In the lower part of the salt scar, sediment is accumulating and the soil surface remains barren of vegetation.

Studies of plant regrowth at a brine-affected site in northwestern Pennsylvania showed that recolonization by hardwood forest occurred rapidly on a completely brine-denuded site where 1) high rainfall followed elimination of the brine source; 2) adjacent forest provided adequate seeds for reestablishment of forest species; and 3) the area was fenced to eliminate browsing

by deer (Walters and Auchmoody, 1989). Similarly, high rainfall (60 inches per year in this area of eastern Kentucky) appears to have flushed salts from the soils rapidly and has permitted rapid revegetation before significant erosion can occur. This is in contrast to sites in Osage County, Oklahoma (Otton and others, 1997a) and southern Illinois (Otton and others, 1997b) where erosion to bedrock has developed at many sites and revegetation is not possible without extensive reclamation.

Plant growth and oil-saturated soil

Shallow oil-saturated soil layers appear to inhibit plant growth at several sites in this study. At Site LC95-1, areas barren of vegetation occur on one of the terraces on the hillslope between the two tank batteries (the old pit site) and at the edge of the wetland (the mudpatch). Shallow holes at the pit and mudpatch site show that they are underlain by layers of oil-saturated clay or sand at depths of 12-15 cm suggesting that oil is toxic to plant growth at these depths or, at least, that oil promotes conditions that inhibit plant growth. In contrast, a hole on the high ground between the small pool and main wetland showed a thick layer of oily clay beneath lush vegetation, but the oily clay was at a depth of 60 cm. Similarly, at Site LC95-2, lush wetland vegetation occurs in the west end of the old brine pond over an oily layer which occurs at a depth of 25 cm. Elsewhere, at Sites LC95-7,9,10, plants are not growing on those portions of soil-covered brine pits where oil continues to seep to the surface.

Radioactivity

Nine of thirteen sites were judged to have subareas with high radioactivity (>260 cps radioactivity on equipment, or >30 pCi/g radium in sludge, scale, or soils), whereas two sites were judged to have moderate radioactivity (>125 cps, but <260 cps radioactivity on equipment, or >5 pCi/g, but <30 pCi/g radium in sludge, scale, or soils), and two sites were judged to have low radioactivity (<125 cps on equipment and <5 pCi/g radium in sludge, scale, or soils). The criteria used here to differentiate high, moderate, and low are related to NORM standards either in use in some states or proposed for other states for radioactivity in equipment (in $\mu\text{R/hr}$) and radium in solids (in pCi/g). The 125 cps used for the upper limit of "low" is equal to 25 $\mu\text{R/hr}$, a value proposed for use by states by the Conference of Radiation Control Program Directors (E. Kray, written commun., 1995). The 260 cps used for the lower limit of "high" radioactivity is equal to 50 $\mu\text{R/hr}$, a value used in Georgia, Louisiana, New Mexico, Oklahoma, South Carolina, and Texas (Peter Gray and Associates, 1996). Thus "low" radioactivity sites described here would be of no regulatory concern under any proposed or existing statute whereas sites designated as "high" may be of concern under any of the proposed or existing statutes. NORM regulations have not been established for the State of Kentucky (Peter Gray and Associates, 1996).

Radium

Radium-rich materials are abundant at site LC95-1. Radium is present in tank sludge in all the water tanks on the site, in disturbed soil layers surrounding the tanks and on the hillslope between the upper tank battery and the road, in scattered patches of disturbed soil in the bulldozed site to the northwest, in sediment on the hillslope and on the floodplain terrace of the small stream adjacent to the bulldozed area, in sediment of the wetland along the small stream, and in sediment at the margins of and possibly beneath the brine pond. Geochemical evidence suggests that most of the radium is associated with barite (high barium and strontium concentrations in analyses), but radioactivity (presumably radium) associated with iron-stained sediment in the wetland along the small stream may be adsorbed on the iron oxyhydroxides (Ames and others, 1983).

Radium has accumulated in soils at the margins of Lake Zachariah where brines were discharged from pipes, flowed down the slope, and entered into the lake. The sediments underlying the bottom of Lake Zachariah also may have accumulated substantial quantities of radium, especially near those points where produced waters are discharged into the lake. The substrate near produced water inflow points at the Loch Katrine wetland complex in Park County, Wyoming has accumulated radium (Ramirez, 1993). Similarly, sediment near the outflow of a tank battery in a marshy area of Grand Bay, Louisiana has accumulated radium (Hanan, 1981; Landa and Reid, 1983).

During this study Ra-226 and Ra-228 data were gathered by the GAD-6-spectrometer at the field sites and by laboratory-based gamma spectrometry on collected soil samples. The Ra-228/Ra-226 activity ratio may provide some insights into the history of NORM additions to soils at a site. The ratio in the sample is influenced by 1) ratio of Ra-228 and Ra-226 in the native soil at the site; 2) the relative proportions of native soil and the added radium-bearing material (sludge or scale) in the soil sample or in the soil volume "seen" by the GAD-6 spectrometer; 3) the initial ratio and the original total activity of Ra-228 and Ra-226 in the added material; and 4) the amount of time since the radium-bearing material was added. Radium-226 has a half-life of 1600 years whereas radium-228 has a half-life of 5.75 years. Thus, over a period of a few decades the amount of radium-228 will drop significantly if the radium-228 is not supported by the decay of thorium-232.

In most native soils, the radium-228 is replaced continuously by the decay of thorium-232 that is also present in the soil however, in almost all brines, the amount of dissolved thorium is extremely small compared to the amount of dissolved radium-228. Thus in the brine and in radium-bearing solids formed from the brine, this radium-228 decays away without being replaced. Where the radium-228 is added to a soil or adsorbed from the brine by the soil, it will decay away and the Ra-228/Ra-226 value will drop by approximately half every 5.75 years. At LC95-1, the Ra-228/Ra-226 values for the samples from the hotspot on the hillslope between the upper tank battery and the road were about 0.07 compared to values of 0.43-0.46 for the samples from the sump and

the mudpatch. Assuming that all of the radium in the solid matter at this site comes from brine waters in the producing zone and that this brine had a constant Ra-228/Ra-226 value through time, then the material from the hotspot has an apparent age a little less than three half lives (about 15 years) older than the material in the sump and mudpatch.

Radium accumulations at site LC95-6 are more modest than those at Site LC95-1 and much closer to background levels. Tank sludge was not observed at the site. Total radium activities measured by the GAD-6 spectrometer ranged from 2.13 to 4.06 pCi/g along the traverse from the tank battery berm downslope to the lower salt scar to 4.38 pCi/g in the wetland further downslope. The Ra-228/Ra-226 values ranged from 1.36 to 1.78 on the hillslope near the tank battery to 0.86 to 1.19 low on the slope near the lower salt scar. The Ra-228/Ra-226 value in the wetland is 0.88. The lowered Ra-228/Ra-226 values for the lower salt scar and the wetland suggest disturbance of the radium isotopes by the passage of the brine, but without uranium and thorium analyses of these samples we cannot determine if excess Ra-228 and Ra-226 are present.

Trace elements

The relative proportion of zirconium and barium in the soil samples appears to provide an index of the percentage of tank sludge present in the soil. Zirconium is a common, highly insoluble constituent of most soils. Barium is a major component of barite, the most common radium-bearing mineral precipitate in tank sludge and scale (Oddo and Thomson, 1994; Raabe, 1996). In two studies related to this one, the median concentration of zirconium in soils in Osage County, Oklahoma was 425 ppm (Otton and others, 1997a) and in southern Illinois the median zirconium concentration was 400 ppm (Otton and others, 1997b). Zirconium concentrations in soils in this study ranged from <10 ppm to 480 ppm. The higher zirconium concentrations occur in the wetland below the tank battery at LC95-6, the least-contaminated sample site in this study based on the lack of discarded tank sludge solids, oil spills, and brine pits. The very low zirconium concentrations occur at sample locations LC95-1H, 1J at Site LC95-1. Assuming that natural soils at this site ought to have 400-500 ppm zirconium and that tank sludge on this site contains less than 10 ppm zirconium the surface soil layers at sample locations 1H and 1J appear to consist solely of weathered tank sludge.

In this study, high concentrations of trace elements other than barium (and strontium) are also limited to sample locations 1H and 1J on the hillslope between the upper tank battery and the road. Here, copper and lead values are the highest seen in the study (Table 4). However, the highest lead concentration (245 ppm) remains below levels of concern for toxicity (400 ppm, United States Environmental Protection Agency, 1994). Cadmium was detected in only one sample (LC95-2A1) at 1 ppm.

Water quality

Two water samples were collected; one each at sites LC95-1 (wetland surface near the brine pond) and LC95-3 (outflow of the Lake Zachariah dam). Total dissolved solids (TDS) and other measured parameters are at levels below drinking water standards (Table 5). The presence of fish in the outflow of the dam contrasts with previous reports and suggests that the water of Zachariah Fork has improved significantly.

At site LC95-1, it seems likely that the brine pond on the flood plain exceeds drinking water standards for total dissolved solids. Conductivity measured 15,600 mS/cm and the TDS is estimated to be 8000 ppm (based on the ratio of TDS to field conductivity in the samples of Table 5). Leakage from the brine pond to the Zachariah fork of Big Sinking Creek is apparently increasing the salinity of the creek but not above acceptable limits. Similarly, downslope seepage from the tank battery on the hillslope is also increasing the salinity of the small stream but not above acceptable standards.

Radium activity occurs at a level near the drinking water standard (5 pCi/L radium-226 plus radium-228) in the sample from the surface of the wetland near the mudpatch. If radium-228 were measured in this sample the standard may be exceeded. Radium in the flow at the dam outlet was low.

Transport of radium

Material interpreted as tank bottom sludges or scale discarded on soils at production sites consistently contains the highest radium levels. As this material ages and weathers, it can be transported downslope by slope-wash and fluvial-transport processes. At site LC95-1, this type of material was deposited on the hillslope between the upper tank battery and the road. Here, the surface soil layer is inferred to consist mostly of tank sludge. Along the road adjacent to this hillslope, radium activity remains elevated and we infer that radium-bearing mineral matter has washed down the slope and then down the road.

Radium-bearing particulates also appear to have been transported downslope from the tank battery area to the mudpatch at the edge of the brine pond. A core hole at the toe of the mudpatch shows layers of sandy sediment with fresh chips of shale (probably from the newly regraded tank battery site), tank sludge fragments (probably from the hillslope with the discarded tank sludge), and carbonate rock fragments (from the graded road surface).

Use of field gamma-spectrometer surveys in assessing NORM

As of mid-1997, eight states have passed rules regulating NORM at oil and gas exploration and production sites (Peter Gray and Associates, 1997); however, only one state, Louisiana, has issued regulations defining how to assess radium contamination at a site (Louisiana Department of Environmental Quality, Radiation Protection Division, 1992). A preliminary site survey using a μ R meter with a grid spacing no greater than 10 m must be performed (if hot spots are present the grid spacing must be 3 m). Soil

sampling is required for any area with survey readings greater than twice background or any area which has an average reading greater than 1.5 times background over an area of 1000 square feet or more. The sample site must be mapped and one or more 100 square meter grids (typically 10 m by 10 m) must be laid out. A minimum of five samples per 100 square meter area must be taken and the top 15 cm layer and the next 15 cm layer must be sampled separately. Sample locations must be noted on the map. The samples must be submitted to a qualified laboratory for analysis. The samples must be analyzed separately and the results averaged for the same depth interval and same 100 square meter area. The criteria for soil contamination by radium are 5 pCi/g of radium-226 or radium-228 above background in the first 15 cm layer averaged over a 100 square-meter area and 15 pCi/g of radium-226 or radium-228 above background averaged over a 100 square-meter area in any 15 cm layer thereafter. No single non-composited sample may exceed 60 pCi/g.

This procedure is time consuming and costly. In addition to labor for required surveying and sampling, analytical expenses are as much as \$200 per sample for both radium-226 and radium-228. Confirmatory analyses are required after removal of the radium-bearing material prior to release of the land. In some cases in Louisiana, such as a pipe-cleaning operation, the Nuclear Energy Division must perform the confirmatory work.

Field gamma spectrometry may offer an alternative to the Louisiana procedures for screening, assessment sampling, or confirmatory work. The initial instrument costs are relatively high (about \$10,000) and the instrument must be calibrated periodically, but these costs would be rapidly recovered after a few site assessments. The instrument records gamma activity from a hemispheric volume of soil about 30-50 cm in radius depending on soil characteristics, thus it does not gather the same type of data specified in the Louisiana regulations. However, simple protocols could be developed that would achieve the same result. Addition of downhole-probe capabilities (not used in this study) would add to the utility of field gamma spectrometry. Data may be rapidly acquired (typically 5 minutes per site after the grid is setup, less if the activity is higher, more if greater precision is required). Use of the instrument also would also permit rapid establishment of "background" radium-226 and radium-228 activity in nearby soils.

Use of the EM-31 conductivity meter in assessing soil salinity

Soil conductivity data were collected at two sites (LC95-1, and LC95-6) during this study. Interferences from cultural features (buried pipe) were significant at site LC95-1 (10 of 22 readings affected), but had less impact at Site LC95-6 (4 of 18 readings affected). At both sites, the 3 m soundings are consistently lower than the 6 m soundings, probably reflecting the presence of more clay or more salinity in the deeper subsurface. At Site LC95-1 background conductivity readings over shale soils were about 36 mS/m (6 m) and 35 mS/m (3 m) whereas over the sandstone soils they were 23 mS/m (6 m) and 16-20 mS/m (3 m). Elevated conductivity readings (58-61 mS/m) occurred in the 6 m

soundings on the hillslope between the upper and lower tank batteries possibly reflecting saline soil caused by the passage of briny waters moving downslope from the upper tank battery in the deeper subsurface. The 3 m sounding at the wetland site gave the highest reading for the entire site (78 mS/m), probably reflecting slightly saline clayey sediment.

At Site LC95-6, conductivity readings throughout the site were generally higher than at Site LC95-1. The highest 6 m and 3 m readings occur in the upper salt scar on the hillslope below the tank battery. There may be a shale layer underlying the tank battery that holds perched saline ground water near the surface. The 6m and 3m conductivity readings in the middle of the lower salt scar are also slightly elevated.

Conductivity readings from the EM-31 provide additional evidence for the presence of slightly saline ground waters at the two sites. Overall the conductivity (salinity) of the shallow subsurface waters seems less than at similar sites in Osage County, Oklahoma (Otton and others, 1997a) and southern Illinois (Otton and others, 1997b).

REFERENCES

- Ames, L.L., McGarrah J.E., Walker, B.E., and Salter, P.F., 1983, Uranium and radium sorption on amorphous ferric oxyhydroxide: *Chemical Geology*, v. 40, p.135-148
- Black, D.F.B., 1978, Geologic map of the Zachariah quadrangle, east-central Kentucky: U.S. Geological Survey map GQ-1452, 1 plate with text.
- Broecker, W.S., 1965, An application of natural radon to problems in ocean circulation, in Ichiye, T., ed., *Symposium on Diffusion in Oceans and Fresh Waters: Lamont Geological Observatory, Palisades, NY.*, pp. 116-145.
- Collins, A.G., 1975, *Geochemistry of oilfield waters*: New York, Elsevier, 496 p.
- Evaldi, R.D., and Kipp, J.A., 1991, Effects of oil production on water resources in the Kentucky River basin, Kentucky: U.S. Geological Survey Water-Resources Investigations Report 90-4191, 58p.
- Fishman, M.J., and Pyen, G., 1979, Determination of selected anions in water by ion chromatography: U.S. Geological Survey Water-Resources Investigations Report 79-101
- Freeman, L.B., 1941, Big Sinking field, Lee County, Kentucky in Levorsen, A.I., ed., *Stratigraphic type oil fields*: Tulsa, Oklahoma, The American Association of Petroleum Geologists, 902 p.
- Hanan, M. A., 1981, *Geochemistry and mobility in sediments of radium from oil-field brines*: Grand Bay, Plaquemines Parish, Louisiana: M.S. Thesis, University of New Orleans, 89p.
- Hebert, M.B., Scott, L.M., and Zrake, S.J., 1995, A radiological characterization of remediated tank battery sites: *Health Physics*, v. 68, n. 3, p. 406-410.
- Jacobs, R.P.W.M., Grant, R.O.H., Kwant, J., Marquenie, J.M., and Mentzer, E., 1992, The composition of produced water from Shell operated oil and gas production in the North Sea in Ray, J.P., and Engelhart, F.R., eds., *Produced Water*: New York, Plenum Press
- Jones D.J. and McFarlan, A.C., 1933, *Geology of the Big Sinking pool, Lee County, Kentucky*: University of Kentucky, Bureau of Mineral and Topographic Survey Bulletin No. 1, 9 p.
- Kraemer, T.F., and Reid, D.F., 1984, The occurrence and behavior of radium in saline formation water in the U.S. Gulf Coast region: *Isotope Geoscience*, v. 2, n. 2, p. 153-174.

- Landa, E.R., and Reid, D.F., 1983, Sorption of Ra-226 from oil-production brine by sediments and soils: Environmental Geology, v. 5, n. 1, p. 1-8.
- Logan, R.W., Beck, G.W., Call, S.M., Houp, R.E., Metzmeier, Lythia, Mills, M.R., Roth, C.A., Schneider, C.C., Walker, D.K., and Westerman, Albert, 1989, Millers Creek drainage biological and water quality investigation for stream use designation: Frankfort, Kentucky, Kentucky Department for Environmental Protection, Division of Water, Ecological Support Section Technical Report No. 25, 93 p.
- Louisiana Department of Environmental Quality, Radiation Protection Division, 1992, Implementation manual for management of NORM in Louisiana: Baton Rouge, Louisiana Department of Environmental Quality, Radiation Protection Division, 18 p.
- McNeill, J.D., 1980a, Electromagnetic terrain conductivity measurement at low induction numbers: Mississauga, Canada, Geonics Limited Technical Note TN-6, 15 p.
- McNeill, J.D., 1980b, Electrical conductivity of soils and rocks: Mississauga, Canada, Geonics Limited Technical Note TN-5, 22 p.
- Michel, J., Moore, W.S., and King, P.T., 1981, Gamma ray spectrometry for determination of radium-228 and radium-226 in natural waters: Anal. Chem., v. 53, pp. 1885-1889.
- Oddo, J.E. and Thomson, M.B., 1994, Algorithms can predict; inhibitors can control NORM scale: Oil and Gas Journal, Jan. 3, 1994, p. 33-37.
- Otton, J.K., Asher-Bolinder, Sigrid, Owen, D.E., and Hall, Laurel, 1997a, Effects of produced waters at oilfield production sites on the Osage Indian Reservation, northeastern Oklahoma: U.S. Geological Survey Open File Report 97-28, 48 p.
- Otton, J.K., Asher-Bolinder, Sigrid, Owen, D.E., and Hall, Laurel, 1997b, Effects of produced water at some oilfield production sites in southern Illinois: U.S. Geological Survey Open File Report 97-448, 99 p.
- Peter Gray and Associates, 1996, Comparison of NORM rules by state: The NORM Report, Spring 1997, p. 28-29.
- Peter Gray and Associates, 1997, Regulations for the control of NORM-update: The NORM Report, Spring 1997, p. 1.

- Raabe, O.G., 1996, Studies of the solubility of naturally-occurring radionuclides in petroleum pipe scale in Proceedings of the NORM/NARM regulations and risk assessment 29th Mid-year Topical Meeting, Health Physics Society, Scottsdale, Arizona, p. 121-128.
- Ramirez, Pedro, Jr., 1993, Contaminants in oil field produced waters discharged into the Loch Katrine wetland complex, Park County, Wyoming and their bioconcentration in the aquatic bird food chain: U.S. Fish and Wildlife Service Contaminant Report Number R6/706C/93, 37 p.
- Rood, A.S., and Kendrick, D.T., 1996, Measurement of ^{222}Rn flux, ^{222}Rn emanation, and ^{226}Ra concentration from injection well pipe scale in Proceedings of the NORM/NARM regulations and risk assessment 29th Mid-year Topical Meeting, Health Physics Society, Scottsdale, Arizona, p. 139-144.
- Saunders, J.A., and Swann, C.T., 1990, Trace-metal content of Mississippi oil field brines: Journal of Geochemical Exploration, v. 37, p. 171-183.
- Stack, Wayne, 1965, Some aspects of waterflooding in the Big Sinking field, Lee County, Kentucky in Wilson, E.N., ed., Proceedings of the technical sessions, Kentucky Oil and Gas Association, twenty-eighth annual meeting, June 4-5, 1964: Kentucky Geological Survey Special Publication 10, 112 p.
- United States Environmental Protection Agency, 1994, Revised interim soil guidance for CERCLA sites and RCRA corrective action facilities: Office of Solid Waste and Emergency Action, U.S. Environmental Protection Agency, Washington, DC., OSWER Directive #9355.4-12.
- Walters, R.S. and Auchmoody, L.R., 1989, Vegetation re-establishment on a hardwood forest site denuded by brine: Landscape and urban planning, v. 17, p.127-133.