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Strontium-90 Contamination in Vegetation from Radioactive Waste Seepage Areas at ORNL, and Theoretical Calculations of ^{90}Sr Accumulation by Deer

C. T. Garten, Jr.
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Environmental Sciences Division
Publication No. 2924

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MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A04; Microfiche A01

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Date Published: June 1987

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

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ACKNOWLEDGMENTS

We wish to thank the following persons for their assistance with various aspects of this work: J. S. Baldwin, E. A. Bondietti, T. W. Burwinkle, J. W. Evans, R. E. Norman, T. G. Scott, B. P. Spalding, and R. I. Van Hook.

ABSTRACT

This report describes data obtained during a preliminary characterization of ^{90}Sr levels in browse vegetation from the vicinity of seeps adjacent to ORNL solid waste storage areas (SWSA) where deer (*Odocoileus virginianus*) were suspected to accumulate ^{90}Sr through the food chain. The highest strontium concentrations in plant samples were found at seeps associated with SWSA-5. Strontium-90 concentrations in honeysuckle and/or blackberry shoots from two seeps in SWSA-5 averaged 39 and 19 nCi/g dry weight (DW), respectively. The maximum concentration observed was 90 nCi/g DW. Strontium-90 concentrations in honeysuckle and blackberry shoots averaged 7.4 nCi/g DW in a study area south of SWSA-4, and averaged 1.0 nCi/g DW in fescue grass from a seepage area located on SWSA-4. A simple model (based on metabolic data for mule deer) has been used to describe the theoretical accumulation of ^{90}Sr in bone of whitetail deer following ingestion of contaminated vegetation.

Based on an assumed 1% usage factor and measured mean concentrations of ^{90}Sr in browse plants from the four seepage areas studied, the calculated ^{90}Sr level in deer bone can easily exceed the confiscation limit of 30 pCi/g for a 45-kg buck that browses contaminated vegetation on a regular basis. The time required to attain a steady-state concentration is expected to be relatively long (more than 2 years). However, calculations, again based on an assumed 1% usage factor and mean plant ^{90}Sr levels, indicate that a 45-kg buck could attain ^{90}Sr concentrations in bone >30 pCi/g after browsing times of 1 week to 1 year.

These model calculations suggest that if 30 pCi ^{90}Sr/g deer bone is to be the accepted screening level for retaining deer killed on the reservation, then 5-pCi ^{90}Sr/g DW vegetation should be considered as a possible action level in making decisions about the need for remedial measures, because unrestricted access and full utilization of vegetation contaminated with <5 pCi/g DW results in calculated steady-state (maximum) ^{90}Sr bone concentrations of <30 pCi/g in a 45-kg buck.

1. INTRODUCTION

During the last 3 months of 1986, the Tennessee Wildlife Resources Agency and the Department of Energy conducted a second year of organized deer hunts on the Oak Ridge Wildlife Management Area for the purpose of controlling deer numbers and mitigating the likelihood of deer-vehicle accidents. Each deer taken by hunters from the Wildlife Management Area was monitored at a checking station for radioactive contamination. Strontium-90 concentration in bone was measured with a scintillation detector applied to a bone sample from the foreleg of each animal. During the 1986 hunt, 29 of 660 deer killed (4.4%) exceeded confiscation limits corresponding to approximately 30 pCi ^{90}Sr/g bone. This compares with 7 of 926 deer killed (0.8%) during 1985 hunts that exceeded such limits.

This report describes data obtained during a preliminary characterization of ^{90}Sr levels in browse vegetation from the vicinity of seeps adjacent to ORNL solid waste storage areas where deer were suspected to accumulate strontium through ingestion of contaminated vegetation. A simple model has been used to describe the theoretical accumulation of ^{90}Sr in deer bone following ingestion of contaminated vegetation. Appendices to this report summarize previously collected or published data on ^{90}Sr contamination in soil and vegetation from the White Oak Creek Watershed. Collectively, this information is intended to help in planning remedial actions that will reduce the frequency of contaminated deer taken in future hunts.

2. METHODS

2.1 SITE SELECTION

Based on published data relating to ^{90}Sr contamination in seepage water or soil, four sites were selected for surveys. Two sites were associated with Solid Waste Storage Area (SWSA) 4: one located on SWSA-4 proper in the vicinity of leaky trenches (termed "bathtub seeps" because the inclination of the trenches allows them to fill with water during rainy periods of the year), and a second located south of SWSA-4 on a floodplain receiving drainage from the burial ground (Fig. 1). Two sites (S-11 and S-5) were located south of SWSA-5 (Fig. 2) at seepage areas previously identified by Duguid[1]. These four sites were selected for immediate study, after the first deer hunts (October) of 1986. A grid was established at each site to facilitate mapping, ground-level radiation surveys with an end-window Geiger-Muller (GM) survey meter, and vegetation sampling.

2.2 GROUND-LEVEL GM SURVEYS

Count-per-minute (cpm) readings were made with an end-window GM survey meter (calibrated by the ORNL Health Physics Division on October 8, 1986) on grid intersections at each site in mid-November 1986. The end-window probe was covered with a plastic bag to prevent instrument contamination and to exclude beta radioactivity from environmental tritium. The probe was held on the ground surface until readings stabilized (usually 30 s). Occasionally, readings were recorded for locations other than grid intersections when the ground-level activity of special surface features (such as embankments or standing water) was of interest.

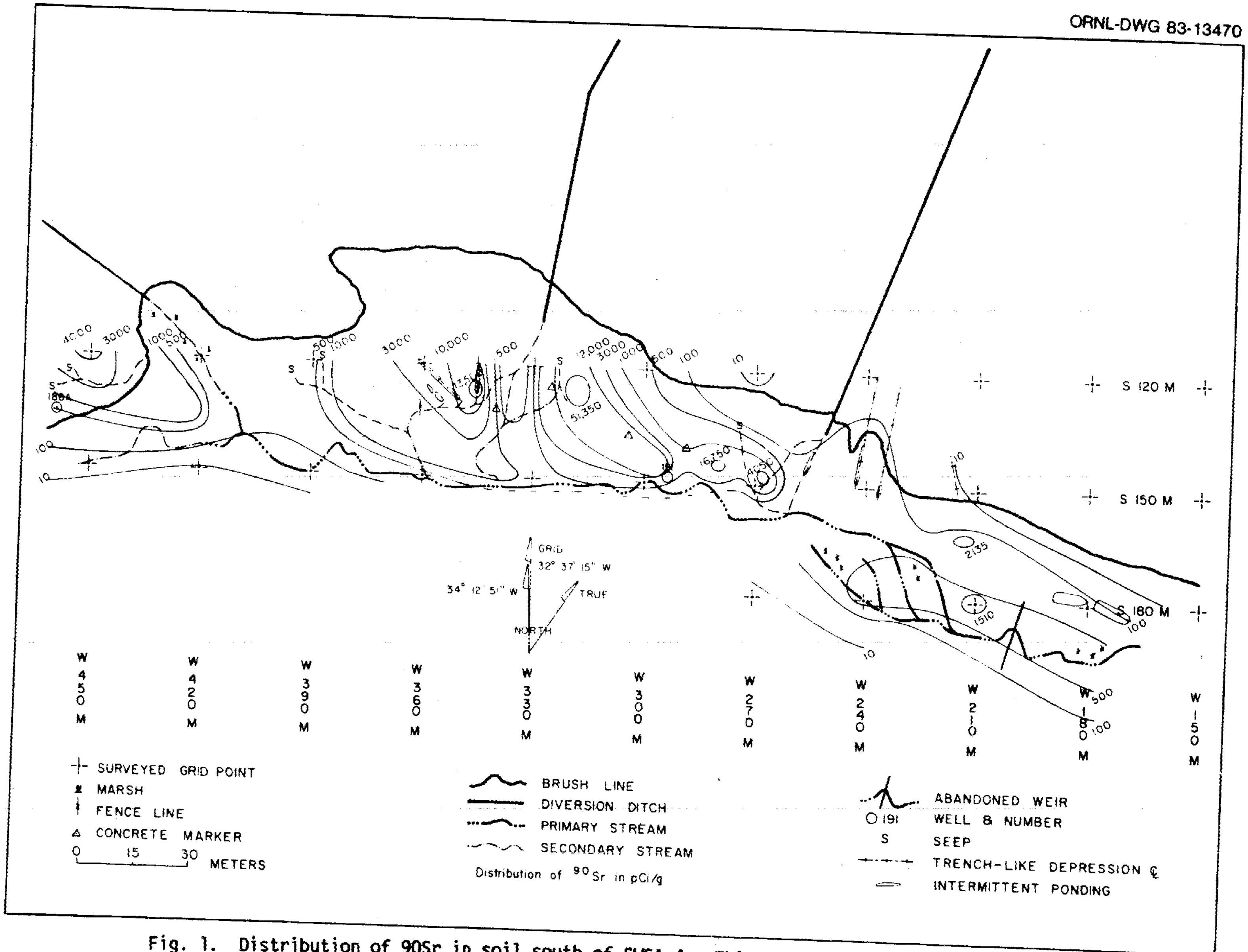

Fig. 1. Distribution of 90Sr in soil south of SWSA-4. This figure was originally published in Melroy et al. (ref. 3) and later reprinted in Davis and Shoun (ref. 14).

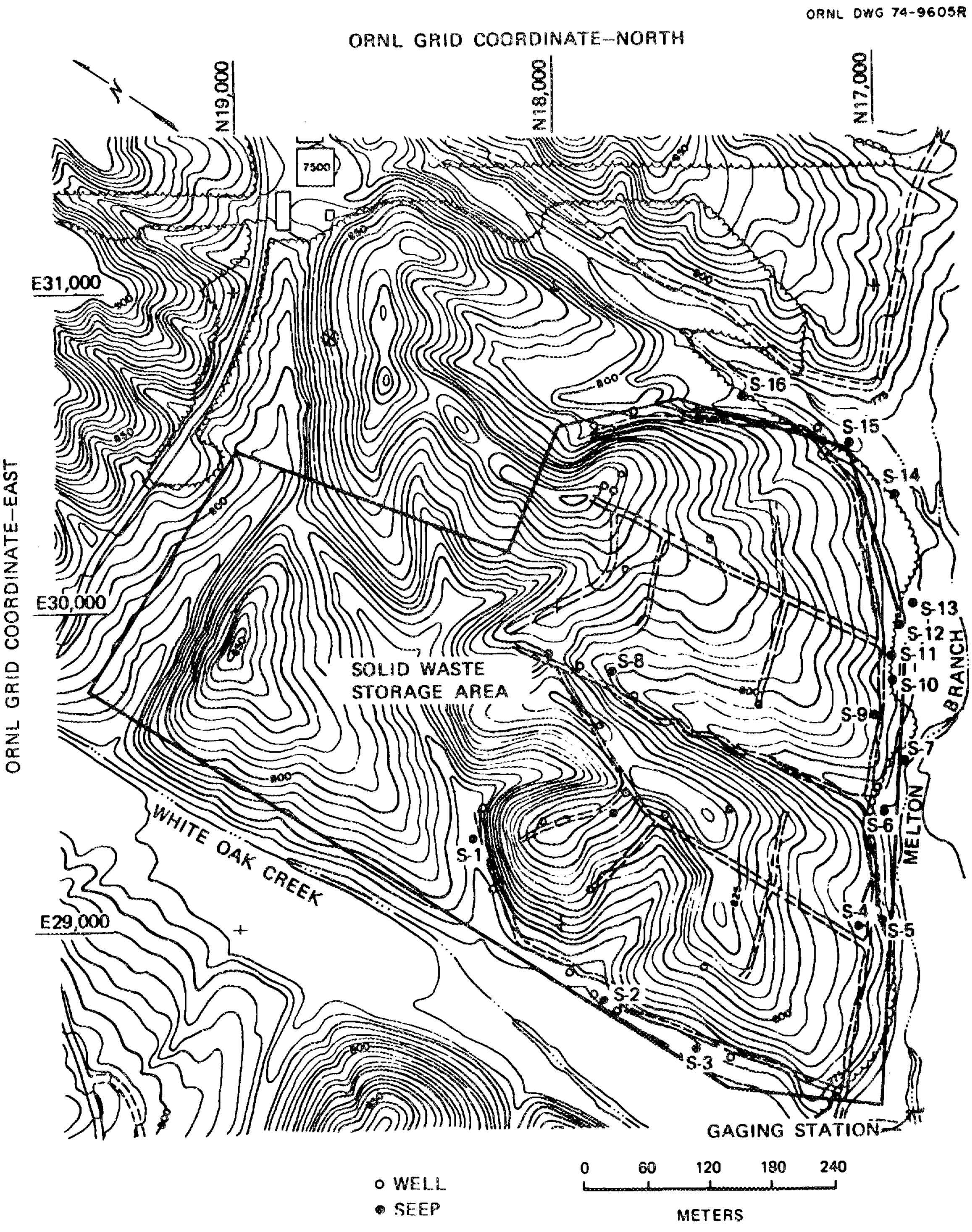

Fig 2. Location of groundwater seeps on the perimeter of SWSA-5 as identified by Duguid (ref. 1).

2.3 VEGETATION SAMPLING

Plant samples (comprised of leaves and stems) were obtained from each site on two different occasions: (1) in early November, 1986, during site visits prior to GM ground surveys, and (2) in mid-November, 1986, during GM ground surveys. Grab samples taken during the first site visit were composited for several different types of fresh vegetation. Following ground-level GM surveys, samples were selected on the basis of count-per-minute readings at each intersection on the grid. Because of the season of the year, most vegetation was not in foliage. Honeysuckle and/or blackberry, both alive in November, were the prevalent browse plants at sites other than the "bathtub seeps" site on SWSA-4. Fescue grass was the dominant vegetation type at the "bathtub seeps.".

2.4 STRONTIUM-90 ANALYSIS

Plant samples were cut with scissors into small pieces, mixed, and ~1 g (fresh weight) was put into a tared crucible. Samples were dried overnight at 100 °C, weighed to obtain the sample dry weight (DW), and ashed in a muffle furnace at 500 °C for 48 h. The ash was dissolved in 1 mL of concentrated nitric acid, the solution was brought to a volume of 10 mL with distilled water, and 4 mL was transferred to a plastic scintillation vial containing 15 mL of distilled water. Vials were analyzed for ^{90}Sr by Cerenkov radiation counting[2]. A ^{90}Sr standard was made to determine counting efficiency. Concentrations were originally expressed as disintegrations per minute (dpm) and later converted to Curies (1 Ci = 2.22 x 10^{12} dpm). Eight samples (after ashing and dissolution in acid) were split for quality assurance purposes: half of each sample was sent to Tom Scott, ORNL Analytical Chemistry Division, for ^{90}Sr analysis by radiochemical methods; the other half was analyzed by Cerenkov radiation counting.

3. RESULTS

3.1 QUALITY ASSURANCE

A paired t-test of the eight split samples showed a statistically significant difference between ^{90}Sr determinations by Cerenkov counting and radiochemical analysis ($t = 2.94$, $df = 7$, $P < 0.05$). Despite a very strong correlation between measurements obtained by us and by the ORNL Analytical Chemistry Division (Fig. 3), Cerenkov counting tended to overestimate the concentration in vegetation by an average of 8.9% (SD = 5.1%). This overestimation was attributed to the presence of other unidentified radionuclides that were not separated from ^{90}Sr prior to Cerenkov counting. Measurements with the ^{90}Sr standard showed that the counting efficiency for Cerenkov radiation from ^{90}Sr on our equipment was 69%.

3.2 SITE CHARACTERIZATION AND GROUND-LEVEL SURVEYS

The highest ground-level count-per-minute readings were encountered at Seep S-11 (Fig. 4) and Seep S-5 south of SWSA-5 (Fig. 5). Seep S-11 lies at the end of a service road on the south side of SWSA-5 near monitoring well T 117-1 (ORNL grid coordinates: N16,983; E29,928). Access to the contaminated area involves descent over a shallow bank just south of the

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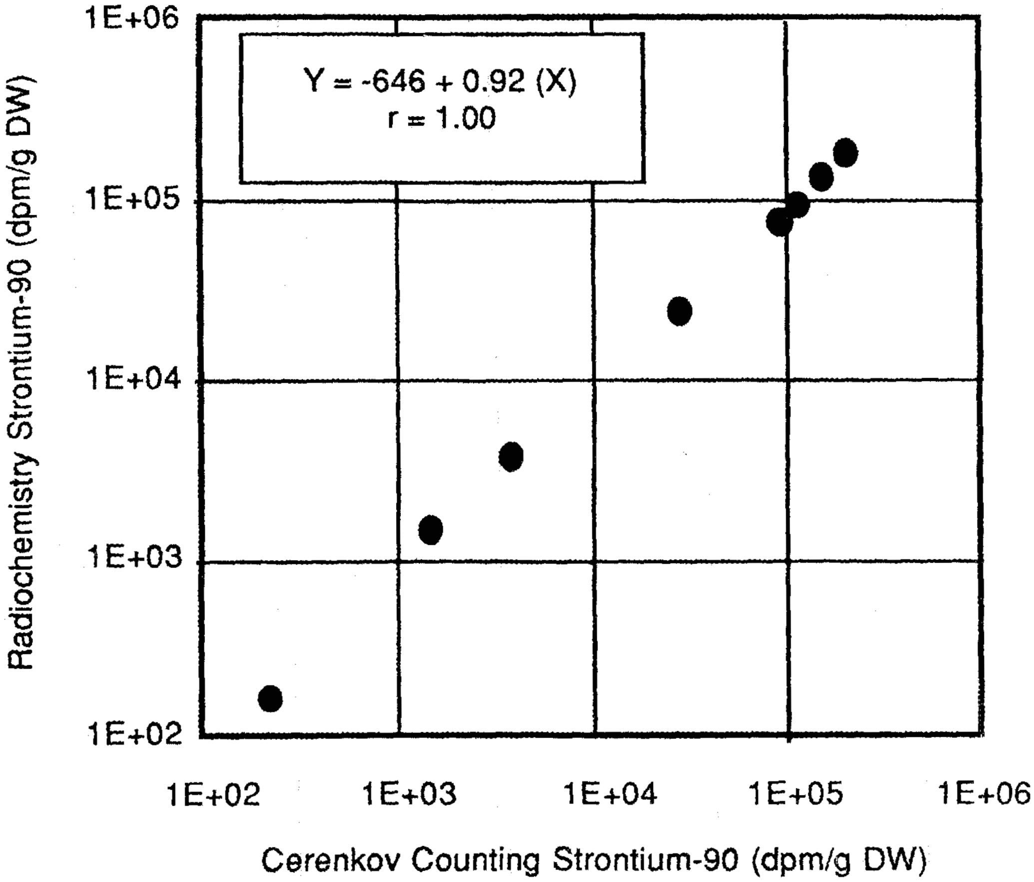

Fig. 3. Correlation between ^{90}Sr concentrations in plants determined by Cerenkov counting (Environmental Sciences Division) and by radiochemical methods (Analytical Chemistry Division).

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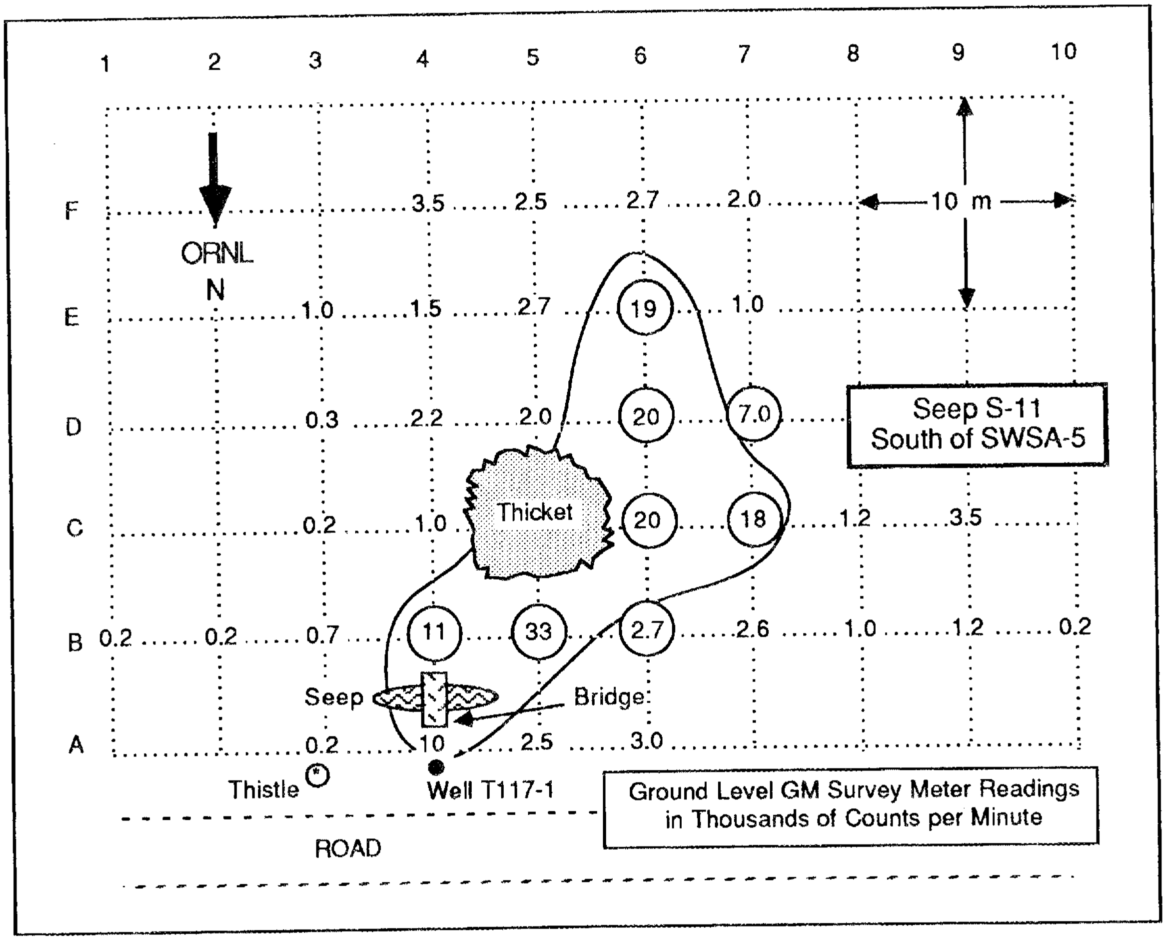

Fig. 4. Map of the study area at seep S-11, adjacent to SWSA-5, showing ground-level GM survey meter readings in thousands of counts per minute at various stations on the sampling grid. Circled GM survey meter readings show where plant samples were collected in November 1986.

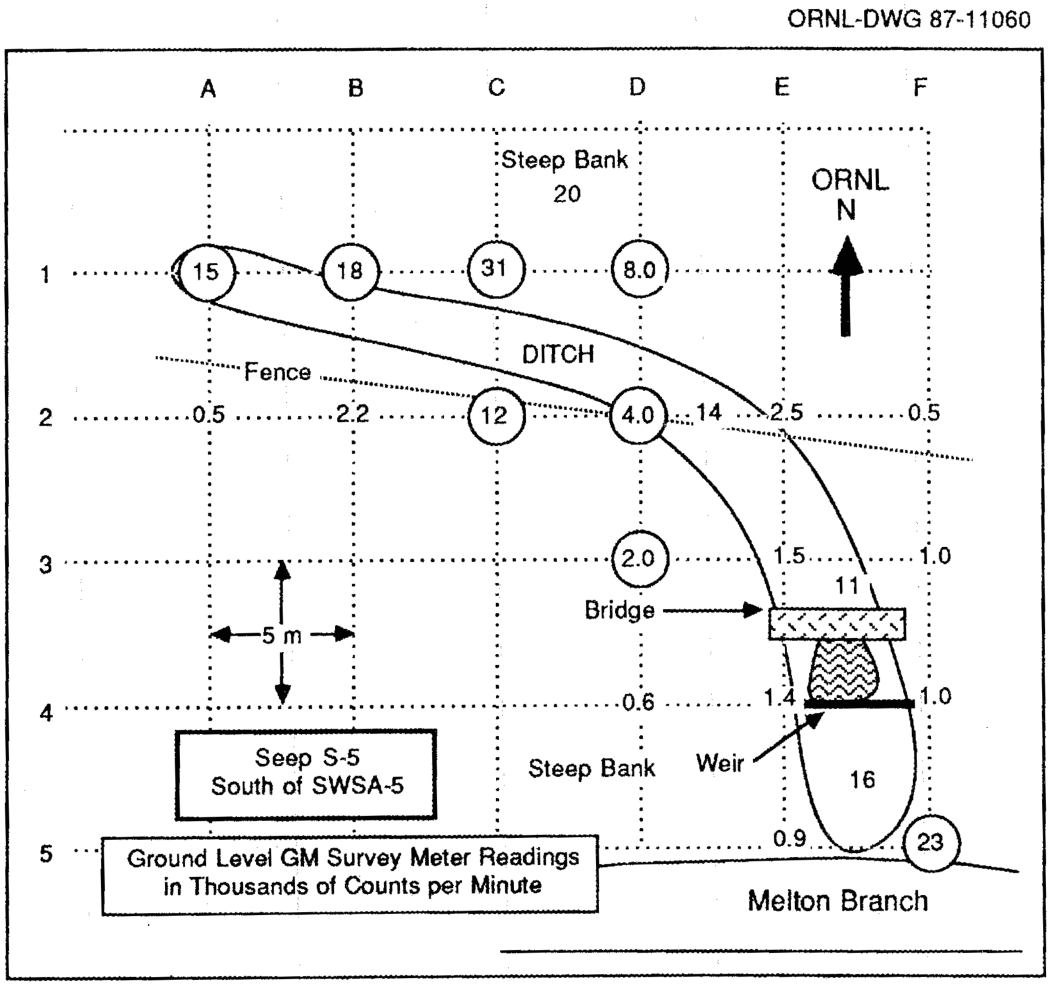

Fig. 5. Map of the study area at seep S-5, adjacent to SWSA-5, showing the ground-level GM survey meter readings in thousands of counts per minute at various stations on the sampling grid. Circled GM survey meter readings show where plant samples were collected in November 1986.

road. Vegetation is principally herbaceous with few trees. A small seep, which contained standing water in November 1986, is crossed by a narrow metal bridge.

Ground-level readings with the end-window GM survey meter were as high as 33,000 cpm immediately south of seep S-11 (Fig. 4). The area of highest ^{90}Sr contamination (preliminarily defined by the ground survey) was <200 m^2. Low level ^{90}Sr contamination may exist on the floodplain south of the seep from the migration of seepage water toward Melton Branch. Other notable features at the S-11 site included: 1) a deer bed and deer droppings in a dense blackberry thicket at grid marker C-5, and 2) a tall, dead thistle plant immediately south of the road gave surface beta-gamma readings of ~7 mR/h (21,000 cpm).

Seep S-5, south of SWSA-5, was also characterized by high ground-level count-per-minute readings (Fig. 5). Contamination at site S-5 is confined to a narrow ditch that is surrounded by steep embankments. There are many large trees on the site with little herbaceous understory. Seepage water was not present in the northernmost portion of the ditch in November 1986; however, standing water was present behind a weir in the southern portion of the ditch before it empties into Melton Branch. The highest ground-level, count-per-minute readings were encountered along the steep embankment bordering the north side of the ditch, as well as along the center course of the ditch from its approximated origin at grid marker A-1 to its confluence with Melton Branch near marker F-5 (Fig. 5).

Ground-level GM survey meter readings encountered at the "bathtub seeps" on SWSA-4 were slightly less than the maximum readings encountered at seeps associated with SWSA-5 [readings near grid markers D-2 and B-2 were 25,000 and 20,000 cpm, respectively (Fig. 6)]. Both seeps had some surface water discolored by iron. The vegetation at this site is low grass and weeds. A well casing identified as 180-A is located near grid marker B-4, and a ditch, which drains to an area south of SWSA-4, crossed the study site in an approximated NW-SE orientation (compass readings were erratic, perhaps because of buried iron). The ditch intercepts a downslope flow from the seeps, and appears to have prevented migration of contamination from its south side (Fig. 6). The estimated level of ^{90}Sr contamination in surface soil in the general vicinity of the "bathtub seeps" is between 1000 and 4000 pCi/g (Fig. 1). Deer have been observed grazing in this area of the burial ground.

Strontium-90 contamination in soil from the seepage area south of SWSA-4 has been previously mapped[3] (Fig. 1). Our survey south of SWSA-4 transected two areas of high surface ^{90}Sr activity (Fig. 7): the ^{90}Sr concentration in soil at grid marker D-9 was ~50,000 pCi/g, and the surface soil concentration at marker D-4 was ~10,000 pCi/g. The westernmost portion of the survey area included two trench-like depressions (one between D-2 and D-3, and one between E-4 and D-4) that contained standing water in November 1986. The eastern portion of the survey area, centered about marker D-9, was drier. The ground-level GM survey meter readings at this site were lower than at any other seepage area surveyed; a maximum reading of 2600 cpm was encountered (Fig. 7). Higher ground-level readings encountered at the "bathtub seeps" were attributed to radionuclides other than ^{90}Sr. The "bathtub seeps" area is

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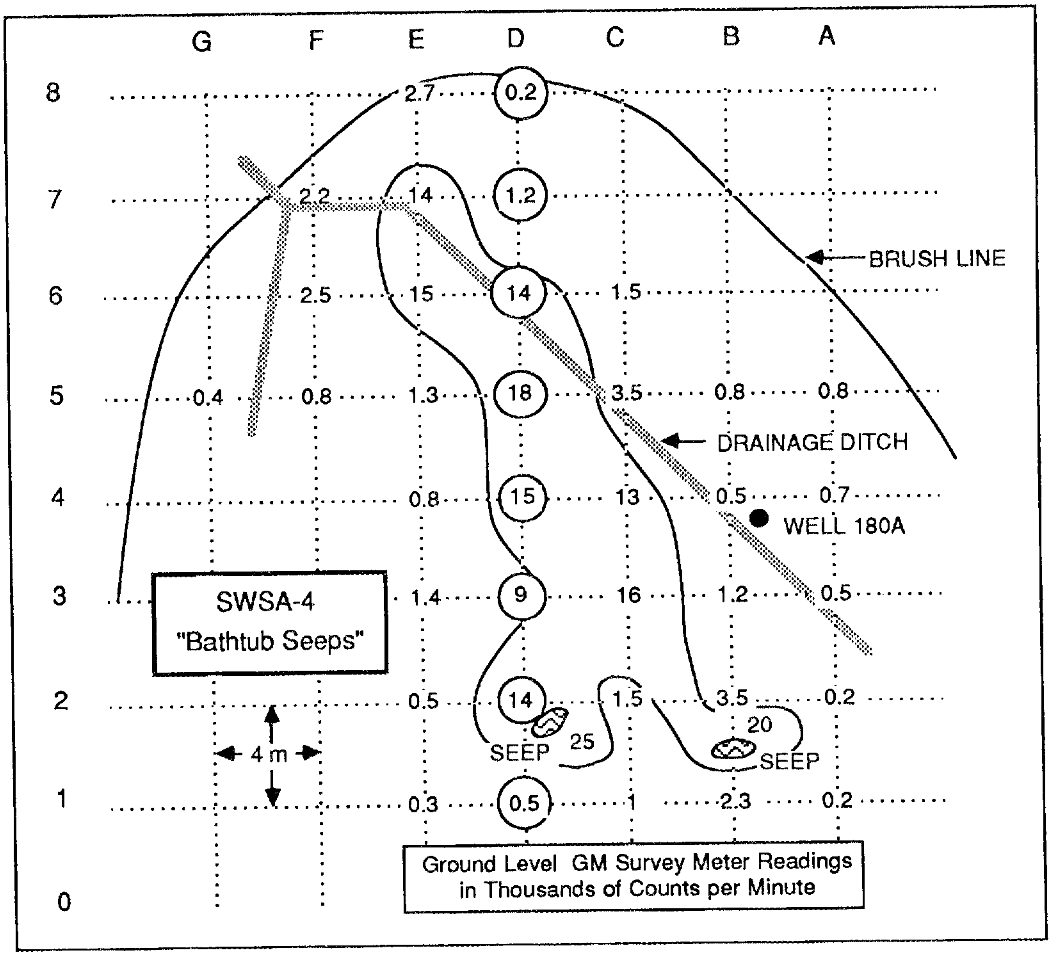

Fig. 6 Map of the study area associated with the "bathtub seeps" on SWSA-4 showing ground-level GM survey meter readings in thousands of counts per minute at various stations on the sampling grid. Circled GM survey meter readings show where plant samples were taken in November 1986.

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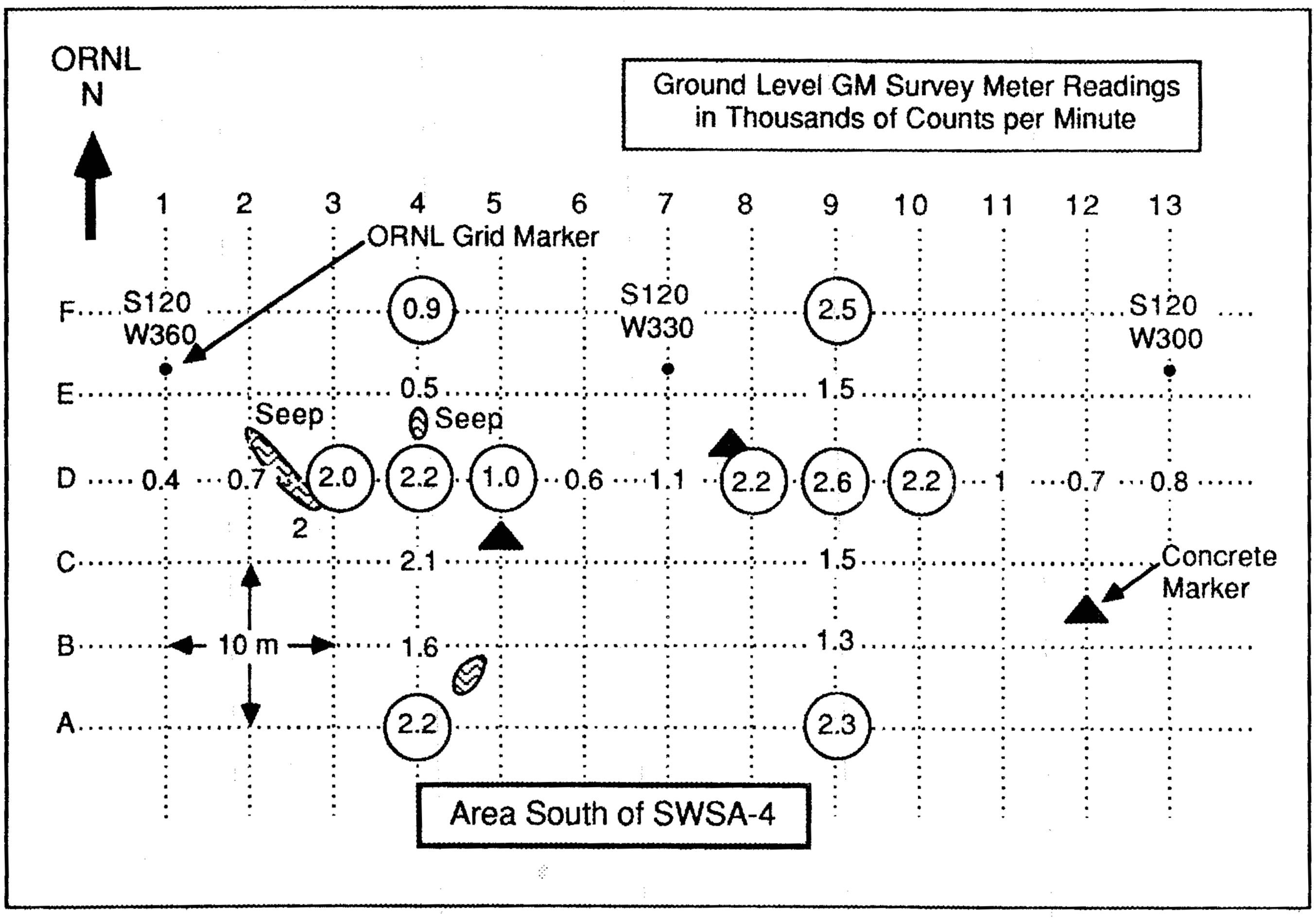

Fig. 7. Map of the study area south of SWSA-4 showing ground-level GM survey meter readings in thousands of counts per minute at various stations on the study area grid. Circled GM survey meter readings show where plant samples were taken in November 1986.

known to contain elevated levels of ^{137}Cs in soil.

There was evidence of deer browsing in vegetation from the study area south of SWSA-4. Deer bedding and evidence of digs were encountered in a nearby seepage area located amidst heavy brush near the ORNL surveyed grid point W 390-S 120 (Fig. 1). The latter seepage area is one of several other identified seeps associated with SWSA-4 (Fig. 1) that were not studied; however, ground-level GM survey meter readings in the vicinity of the ORNL surveyed grid point W 390-S 120 were <300 cpm.

3.3 STRONTIUM-90 LEVELS IN PLANT SAMPLES

The highest concentrations of ^{90}Sr in plant samples were found at seepage areas associated with SWSA-5 (Fig. 8). Strontium-90 concentrations in honeysuckle and/or blackberry shoots from seeps S-11 and S-5 averaged 39 and 19 nCi/g DW, respectively. The maximum concentration observed was 90 nCi/g DW in honeysuckle collected south of seep S-11 (Appendix A).

Strontium-90 concentrations in honeysuckle and blackberry shoots collected south of SWSA-4 averaged 7.4 nCi/g DW (Fig. 8). Concentrations ranged between 9 and 21 nCi/g DW on the western portion of the transect where surface soil ^{90}Sr concentrations were estimated to be between 12 and 50 nCi/g. The lowest average concentration was encountered in fescue grass from the "bathtub seeps" area on SWSA-4: 1 nCi/g DW (Fig. 8).

Correlations between ^{90}Sr concentrations in plants and ground-level GM survey meter readings were not statistically significant ($P > 0.05$) within each study area, except in the study area associated with seep S-11 where the correlation coefficient was 0.82 (df = 6). This correlation was

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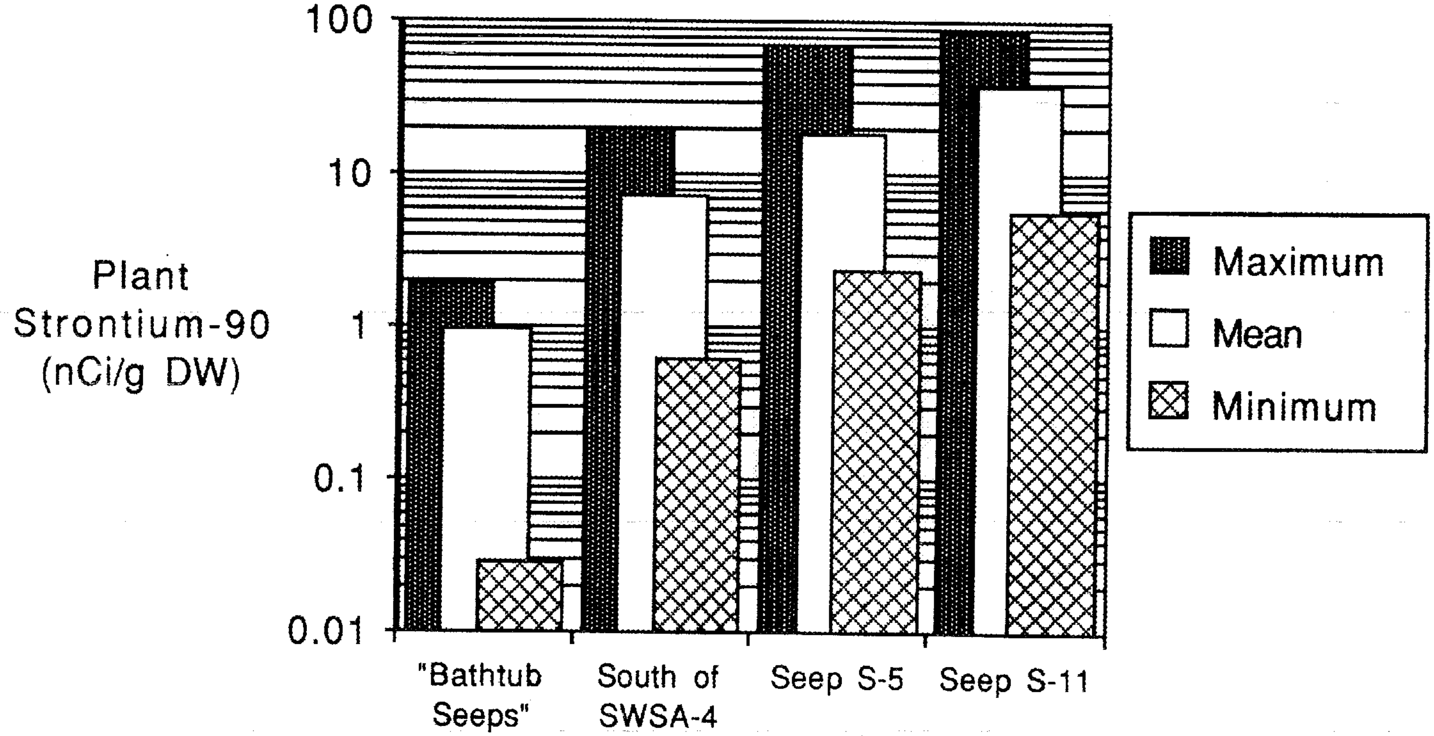

Fig. 8. Maximum, mean, and minimum ^{90}Sr concentrations in plant samples from the four study areas (see Appendix A for a complete listing of data).

significant because of three discrete groups of data (Fig. 9). Fig. 9 shows that over the sites examined, ground-level readings with the GM survey meter were weakly correlated with ^{90}Sr concentrations in plants ($r = 0.65$, $P < 0.001$).

4. FOOD CHAIN MODEL

A simple model of ^{90}Sr accumulation in deer was derived from data for strontium metabolism in mule deer ranging in age from 8 to 36 months[4]. Whitetail deer are similar to mule deer in body size and habits, except that whitetail deer prefer forest habitats.

4.1 STEADY-STATE CALCULATIONS

The steady-state skeletal concentration of ^{90}Sr in deer from continuous ingestion of contaminated vegetation can be estimated from the following equation:

$$S = [(I * a) / E] / m \qquad (1)$$

where

S = skeletal concentration (pCi/g),

I = daily ingestion (pCi/d),

a = fractional assimilation from the deer GI tract,

E = elimination constant (per day), and

m = skeletal mass (g DW).

This equation assumes that, following ingestion and absorption into the bloodstream, ^{90}Sr is partitioned entirely to the skeleton. This is a

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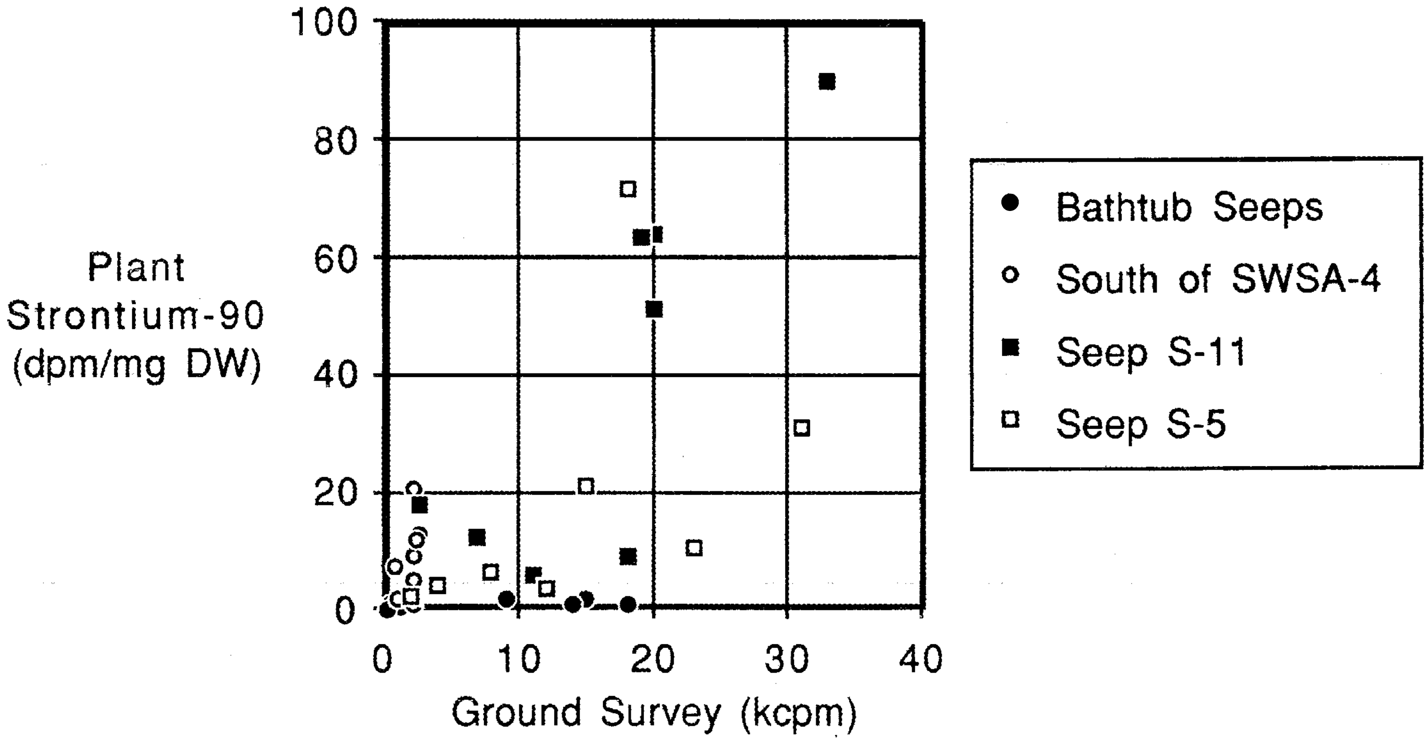

Fig. 9. Relationship between ground-level GM survey meter readings and corresponding plant ^{90}Sr concentrations for the seepage areas.

reasonable and conservative assumption since ^{90}Sr is known to be a bone-seeking radionuclide.

Daily ingestion of ^{90}Sr can be estimated from the following equation:

$$I = c * r * u \qquad (2)$$

where

c = plant concentration (pCi/g DW),

r = ingestion rate (g DW/d), and

u = usage factor, or the fraction of diet from seepage areas.

4.2 NON-STEADY-STATE CALCULATIONS

The skeletal concentration of ^{90}Sr in deer bone, after a given time interval of feeding on contaminated vegetation, can be estimated from the following equation:

$$S_i = \{ [(I * a) / E] * (1 - e^{-Et}) \} / m \qquad (3)$$

where

S_i = the ^{90}Sr concentration in deer bone after time t,

I = c * r * u, and

t = the number of days that the contaminated diet is utilized.

4.3 MODEL PARAMETERS

4.3.1 *Ingestion Rate* (r)

The amount of vegetation ingested is a function of body weight, sex, and season. In models of ^{90}Sr accumulation by mule deer, Schreckhise and Whicker[4] used a daily ingestion rate of 16.5 g DW vegetation/kg body weight for bucks, and between ~18 and 22 g vegetation/kg body weight for does. For the present calculations, we can assume an average ingestion rate of 17 g DW vegetation/kg body weight/day in whitetail deer; the ingestion rate is multiplied by deer body weight (kg) to obtain grams dry weight ingested per day.

4.3.2 *Fractional Assimilation* (a)

Schreckhise and Whicker[4] found that the fractional assimilation of strontium from the GI tract varies between bucks (a = 0.128) and does (a = 0.0377). Gender differences and seasonal variation in assimilation are apparently related to changing mineral requirements during antler development.

4.3.3 *Elimination Constant* (E)

For bucks and does, the elimination constant for strontium in mule deer is 0.00355 and 0.00401 per day, respectively[4]. An average elimination constant of 0.0038, corresponding to a biological half-life of 182 d, was assumed for the purpose of the present model. Schreckhise and Whicker[4], report that there is evidently a large amount of skeletal bone mobilized during antler development in males. An alternative turnover rate for ^{90}Sr in deer bone of 0.00026 per day (7.3 year biological half-life) suggested by Farris[5] does not appear to be realistic in view of model validation work presented by Schreckhise and Whicker[4].

4.3.4 *Skeletal Mass* (m)

A value of 0.103 was used as the skeleton to total deer body weight ratio, or 10.3% of the total body weight was skeletal mass[4].

4.4 MODEL CALCULATIONS

Table 1 shows an example calculation for the steady-state concentration of ^{90}Sr in bone from a 45-kg (100-lb) deer. The calculation is based on a plant ^{90}Sr concentration of 39,000 pCi/g (the average for seep S-11) and an assumed usage factor of 1%. A usage factor of 1% implies that deer daily ingest ~8 g DW of contaminated vegetation. The steady-state ^{90}Sr concentration in females is less than that in males because of the gender difference in assimilation efficiency of strontium from the GI tract. Calculations of ^{90}Sr concentrations in doe bones must be interpreted with caution because the model described by Schreckhise and Whicker[4], on which these calculations are based, did not adequately predict observed ^{90}Sr values in female mule deer. Parameter values for does are based on only 5 females, and the effect of lactation and other variables on the model parameters is unknown. By comparison, parameter values for males are based on 17 deer.[4]

Based on a 1% usage factor and mean concentrations of ^{90}Sr in plants from the four seepage areas studied, calculations indicate that the ^{90}Sr level in bone from a 45-kg buck can easily exceed the confiscation limit of 30 pCi/g for bucks that browse vegetation on a continuing basis (Table 2). However, because of the assumed 182 d biological half-life for ^{90}Sr in deer, an exposure period of more than 2 years (26 months) would be necessary for concentrations to reach 95% of the steady-state bone concentrations presented in Table 2. Therefore, the calculated (non-steady-state) bone concentration of ^{90}Sr in bucks after varying intervals of

Table 1. Example steady-state calculation of ^{90}Sr concentration in deer bone

Item	Symbol or Equation	Units	Male	Female
Plant concentration[a]	c	pCi/g	39,000	39,000
Deer body weight	BW	kg	45.3	45.3
Daily ingestion[a]	i	g/kg BW/d	17	17
Ingestion rate[a]	r = W * i	g/d	770	770
Usage factor	u	%	1	1
Estimated intake	I = c * r * u	pCi/d	300,339	300,339
Assimilation fraction	a		0.128	0.038
Elimination constant	E	per day	0.0038	0.0038
Skeletal mass:body weight	ratio	%	10.3	10.3
Skeletal mass	m	g	4,666	4,666
Steady state Bone concentration	S = [(I * a)/E]/m	pCi/g	2,168	644

[a] dry weight basis.

Table 2. Mean plant ^{90}Sr concentration and calculated concentration in deer bones after different intervals of food chain exposure

Item	Bathtub seeps	South SWSA-4	Seep S-5 SWSA-5	Seep S-11 SWSA-5
Mean plant ^{90}Sr Concentration (pCi/g)	1,000	7,400	18,800	39,100
^{90}Sr concn. (pCi/g) in bone[a]				
After 1 week	1	11	27	57
After 2 weeks	3	21	54	113
After 1 month	6	44	113	234
After 3 months	16	120	306	635
After 6 months	28	206	524	1,089
After 1 year	42	309	784	1,630
Steady-state concn.	56	441	1,045	2,168

[a] Calculation for a 45-kg (100-lb) buck, assuming 1% of the diet is contaminated vegetation.

food chain exposure, is also presented in Table 2. For seeps S-11 and S-5, calculated ^{90}Sr concentrations in deer bone can exceed 30 pCi/g after 2 weeks of food chain exposure. For the seepage area south of SWSA-4, ~1 month of food chain exposure was required before calculated bone concentrations exceeded the confiscation limit.

The usage factor in the model has a proportionate influence on calculations of bone ^{90}Sr in deer bone (i.e., a doubling of the usage factor will double the calculated concentration). A usage factor of 1% has been assumed in prior calculations, but the validity of this assumption is unknown because the extent to which deer utilize the seepage areas for food has not been determined. Assuming maximum usage (100%), calculations show that a ^{90}Sr concentration of <5 pCi/g DW in vegetation results in calculated steady-state concentrations of <30 pCi/g in deer bone. A ^{90}Sr concentration of 5 pCi/g DW in vegetation is ~25 times higher than background ^{90}Sr levels from weapons testing fallout.

There are infinite numbers of possible combinations of ^{90}Sr plant concentrations and usage factors that contribute to ^{90}Sr levels in deer bone; consequently, Fig. 10 and 11 were prepared to show those combinations that result in calculated bone concentrations exceeding 30 pCi/g under steady-state and non-steady-state conditions, respectively. For a 45-kg buck, more than 1% continuous usage of vegetation from the seeps examined, and more than 6% continuous usage of vegetation containing relatively low levels of ^{90}Sr (100 pCi/g) results in calculated steady-state concentrations in bone that exceed 30 pCi/g (Fig. 10). Similar calculations for non-steady-state conditions (after 1 week of food chain

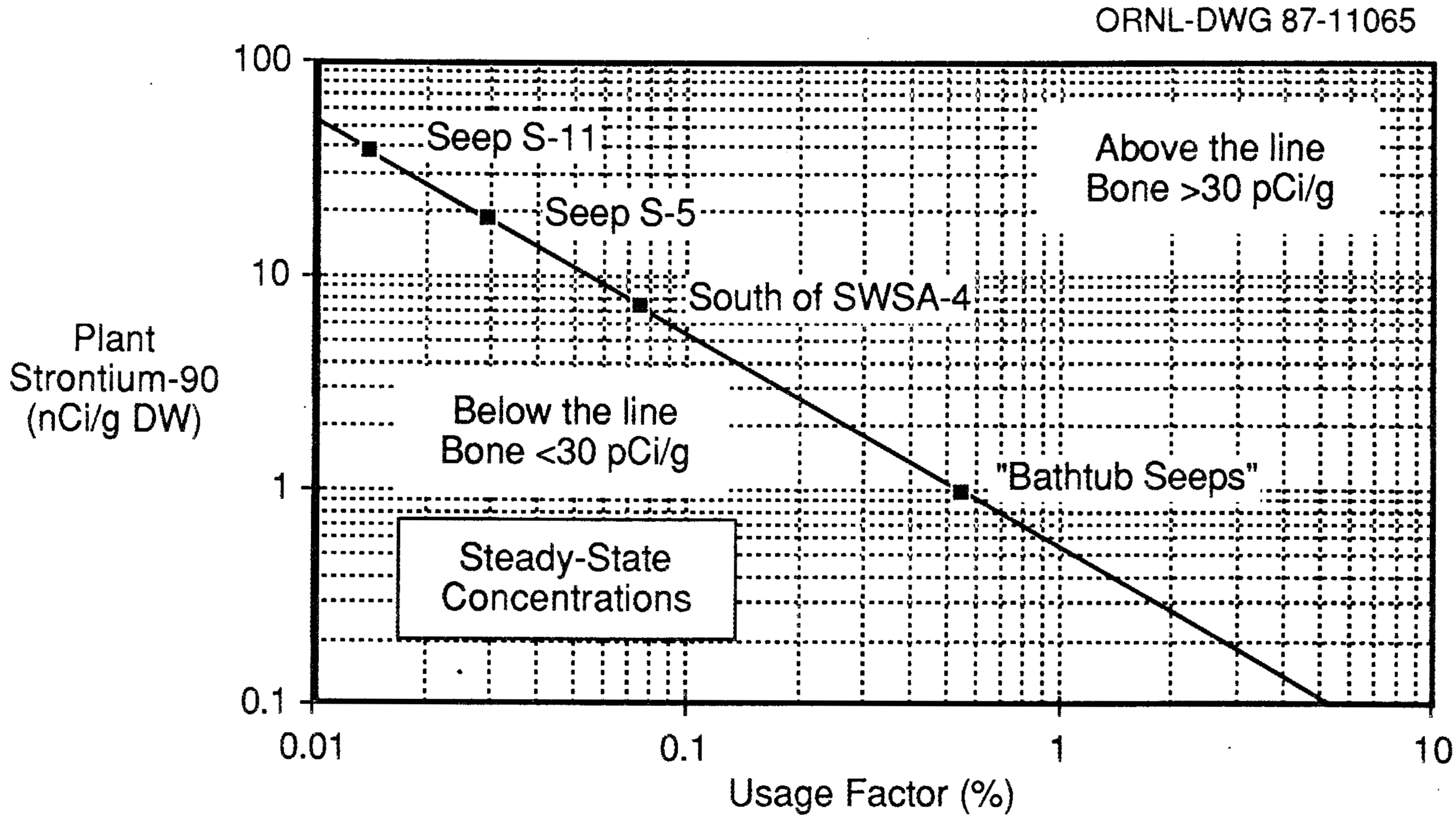

Fig. 10. Combinations of usage factor and plant ^{90}Sr concentration that result in calculated steady-state ^{90}Sr levels in deer bone more than (above the line) or less than (below the line) 30 pCi/g. Points on the line correspond to plant concentrations at the study areas and the usage factor necessary to result in a calculated ^{90}Sr concentration in bone of 30 pCi/g.

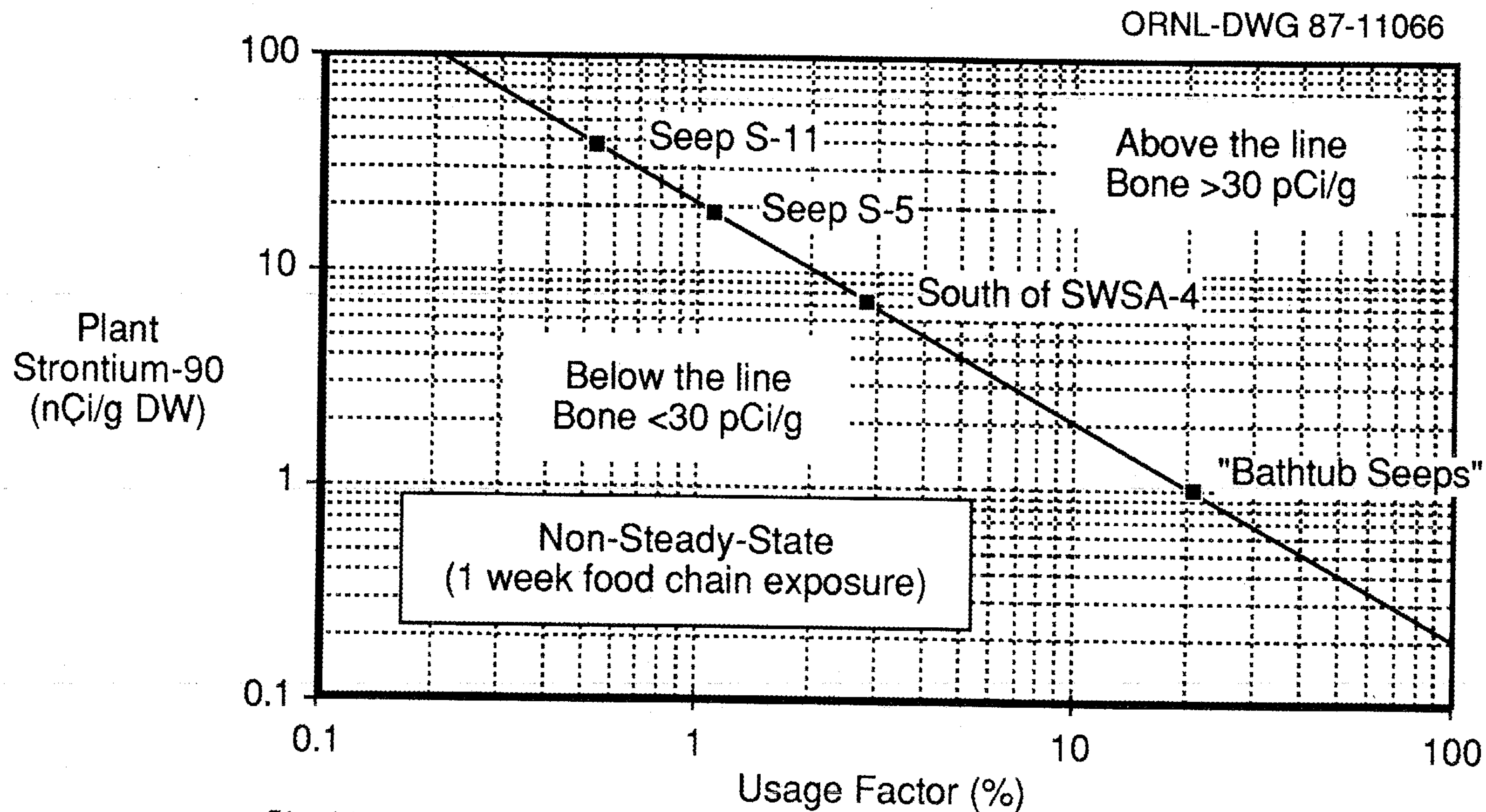

Fig. 11. Combinations of usage factor and plant ^{90}Sr concentration that result in calculated ^{90}Sr levels in deer bone more than (above the line) or less than (below the line) 30 pCi/g after 1 week of food chain exposure. Points on the line correspond to plant concentrations at the study areas and the usage factor necessary to result in a calculated ^{90}Sr concentration in bone of 30 pCi/g.

exposure) show that more than 4% usage of vegetation from the three more highly contaminated seepage areas (S-11, S-5, and south of SWSA-4) results in calculated bone concentrations exceeding 30 pCi/g (Fig. 11).

5. SOIL-TO-PLANT TRANSFER OF STRONTIUM-90

In the late 1950's, ^{90}Sr was recognized as a potential accumulator in terrestrial ecosystem components of the White Oak Lake bed. Mean concentrations in grasses, forbs, and woody plants occupying the lake bed from 1956 to 1960 were 0.31, 0.77, and 0.56 nCi/g DW, respectively[6]. Strontium-90 concentrations were higher in leaves than in stems and higher in forbs and woody plants than in herbaceous plants. DeSelm and Shanks[6] estimated that approximately 7% and 2% of the soil strontium was removed by lake bed willows and herbaceous vegetation, respectively. Much of this removal was recycled back onto the topsoil as accumulated litter.

Baes et al.[7] reviewed existing literature on the plant:soil concentration ratios of various radionuclides. The range of reference mean values for the plant:soil concentration ratio of ^{90}Sr was 0.077 to 17, with a geometric mean of 2.7. Variability in the ratio arises from regional variation in soil parameters affecting ^{90}Sr uptake by plants. The foremost soil property affecting uptake by plants is the status of exchangeable calcium in soil. Plant concentrations decrease with increasing exchangeable soil calcium. Other soil properties, like pH, texture, and organic matter, can become important in determining ^{90}Sr uptake by plants in neutral or alkaline soils or in soils where more than 70% of the exchange capacity is calcium saturated[8]. The relationship between ^{90}Sr levels in soil and plants is complex and usually governed by site-specific conditions.

There is little empirical data from which to derive representative plant:soil concentration ratios for ^{90}Sr in the White Oak Creek Watershed. Surface soils of the Tennessee ridge and valley province are typically acidic (pH between 5.5 and 6.5), and in general, the plant uptake of ^{90}Sr is greater from acid soils (pH <6)[8]. Table 3 summarizes existing data on plant:soil concentration ratios for ^{90}Sr in watershed soils that are neutral or slightly alkaline. The alkalinity is attributed to waste treatment (e.g. the alkaline precipitation of ^{90}Sr) prior to releases to White Oak Creek.

A plant:soil concentration ratio of ~1.5 is representative of ^{90}Sr uptake by herbaceous plants from the White Oak Lake bed and the White Oak Creek floodplain (Table 3). Based on data presented by DeSelm and Shanks[6], the ratio may be greater for forbs and woody browse vegetation growing on more acidic soils in the watershed. Research is needed to empirically determine the plant:soil concentration ratio for ^{90}Sr in a variety of vegetation types from the watershed, so that sites requiring remedial action can be confidently identified on the basis of ^{90}Sr levels in soil when plants are not present.

6. DISCUSSION

Model calculations for the accumulation of ^{90}Sr in deer bone, as outlined in this report, are highly theoretical and should not be interpreted as reality, because parameter values from metabolism studies with mule deer have been adapted to calculations for whitetail deer. Strontium-90 uptake and metabolism by deer are related to the quality and quantity of diet, age, sex, and physiological condition[4,9]. The physiological parameters

Table 3. Strontium-90 plant:soil concentration ratios reported from studies done in the White Oak Creek Watershed

Plant type	^{90}Sr Soil (nCi/g DW)	Plant:Soil concentration ratio	Notes	Reference
German Millet (*Setaria italica*)	0.255	2.3	a	1
Sudan Grass (*Sorghum* sp.)	0.255	1.9	a	1
Orange Fodder Cane (*Sorghum vulgare*)	0.255	0.6	a	1
Corn (*Zea mays*)	0.310	1.3	b	2
Herbaceous species	0.360	3.3	c	3
Unidentified grasses	0.175	0.9-1.6	d	This report (Appendix B)

a) From White Oak Lake bed agricultural plot, soil pH = 7.1.
b) Concentrations in leaves from White Oak Lake bed agricultural plot.
c) Includes following plants: *Polygonum, Bidens, Eupatorium,* and *Juncus*
d) From White Oak Creek floodplain, soil pH = 7.5.

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that govern ^{90}Sr uptake and retention by female mule deer are not well quantified, and the extent to which parameters vary between mule deer and whitetail deer is unknown. To avoid uncertainties and to normalize comparisons between seepage areas, the calculations presented here have been made for a "standard" deer (45-kg, male). Despite these limitations, the calculations are useful as first approximations for guidance in planning remedial actions to prevent the food chain transport of ^{90}Sr to ORNL deer.

The accumulation of ^{90}Sr in deer depends even more strongly on the extent to which deer actually utilize vegetation from the seepage areas in their diet. Utilization of the seepage areas depends on elements of animal behavior that cannot be adequately represented in the food chain model used in this report However, calculations indicate that a food chain exposure of 7 d duration and more than 4% utilization of vegetation from seep areas S-11, S-5, or the area south of SWSA-4 can produce calculated concentrations of ^{90}Sr in deer bone in excess of 30 pCi/g (Fig. 11).

Calculations also indicate that even the modest (~10%) inclusion in the deer diet of vegetation contaminated with relatively low levels (~100 pCi/g) of ^{90}Sr can result in steady-state concentrations of this isotope in deer bone exceeding 30 pCi/g. The time required to attain a steady-state concentration is expected to be relatively long (more than 2 years assuming a biological half-life of 182 d); however, given sufficient time, long-term low-level exposure can result in a degree of ^{90}Sr accumulation by deer that might necessitate confiscation. Back calculations, for a 45-kg buck, show that 100% usage of browse vegetation containing a ^{90}Sr level of ~5 pCi/g DW is the maximum plant concentration that will not result in steady-state

^{90}Sr concentrations in bone >30 pCi/g.

Research is needed on land management practices, such as habitat modification or soil treatments, that might be effective in deterring deer from contaminated areas or reducing the plant uptake of ^{90}Sr, because it may be too expensive or difficult to remove contamination or to exclude deer by fencing larger (nonpoint-source) areas of low-level contamination. For example, superphosphate fertilizer treatments have been shown to reduce the ^{90}Sr uptake by Sorghum grown on the upper White Oak Lake bed[10]. Various other treatments that are known to affect the cation-exchange capacity of the soil, can also alter the ^{90}Sr uptake by plants[8], thereby reducing or increasing its food chain transport. The application of soil treatments as a remedial action measure must be carefully researched, because the effectiveness of soil amendments depends upon soil acidity and base saturation[8].

The possibility of habitat modification as a remedial action measure, such as the progressive reduction of forest coverage throughout contaminated portions of the watershed, should be evaluated in the context of an overall long-term land management plan for White Oak Creek Watershed.

The use of seeps for drinking water is another potential source of ^{90}Sr available to deer aside from seepage area vegetation. Concentrations of ^{90}Sr in seep water and plant samples for three of the four sites examined are compared in Table 4. The data are more than 10 years apart, but mean concentrations in vegetation during 1986 exceed the reported concentrations in seep water at each site in 1975. The maximum

Table 4. Comparison of ^{90}Sr concentrations in seep water and seepage area vegetation.

		^{90}Sr concentration		
Location	Seep	Seep water[a] (dpm/mL)	Vegetation Mean[b] (dpm/g DW)	Vegetation:water ratio
South of SWSA-4	S-2	451	16,440	36
SWSA-5	S-5	348	41,730	120
	S-11	23	86,802	3,774

[a] Data from Duguid, J. O. 1975. Status report on radioactivity movement from burial grounds in Melton and Bethel valleys. ORNL-5017. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[b] Data from 1986.

concentrations in vegetation at each site exceed those in seep water by factors between 100 and 8550. The vegetation:water ratio undoubtedly varies, depending on the seep examined and the time of collection; therefore the importance of seep water as a source of ^{90}Sr to deer is difficult to assess because of changing circumstances of exposure. However, for the seeps examined in this study, the ingestion of contaminated vegetation by deer is considered the more important source of ^{90}Sr.

7. CONCLUSIONS AND RECOMMENDATIONS

1. The two seeps south of SWSA-5, S-11 and S-5, are a higher priority for remedial action than the seeps associated with SWSA-4. The areas of high-level (>1000 pCi/g DW) ^{90}Sr contamination in vegetation at seeps S-11 and S-5 are relatively small (<1000 m^2) and could be excluded from deer by fencing. For worker safety, a health physicist should be consulted before construction activities begin, because fragments of airborne vegetation may constitute an inhalation hazard because of the high concentrations of ^{90}Sr (the maximum observed was 200 dpm/mg DW). There are other seeps adjacent to SWSA-5 that were identified by Duguid[1] and further characterized by Spalding and Munro[11] (Fig. 2); however, these areas have not been examined for ^{90}Sr levels in vegetation. Some seeps that have not been surveyed have ^{90}Sr levels in seep water exceeding those present at seep S-5 and S-11[11].

2. The area of ^{90}Sr contamination south of SWSA-4 is more extensive (Fig. 1) and concentrations in vegetation are less than those encountered in

seepage areas adjacent to SWSA-5. However, in terms of priority for remedial action, the seeps associated with SWSA-4 (both the "bathtub" seeps and those south of SWSA-4) are only slightly less important than seeps adjacent to SWSA-5, because there is apparently heavy use of SWSA-4 by deer. This evidence includes frequent sightings of deer on SWSA-4 as well as the presence of deer beds and digs in brushy areas adjacent to the burial ground. Assuming a 1% usage factor, calculations show that a food chain exposure of ~1 month in areas south of SWSA-4 results in calculated ^{90}Sr levels in deer bone of >30 pCi/g.

3. Additional areas of environmental ^{90}Sr contamination in the White Oak Creek Watershed should be identified and surveyed for ^{90}Sr contamination. Prior reports on the areal distribution of ^{90}Sr activity in streambed gravels from the watershed[12,13] and from seeps associated with SWSA-4 and SWSA-5[1,11,14,15] indicate that these areas fall into the following broad categories:

- seeps associated with solid waste disposal areas that have been previously identified and are suspected or known sources of ^{90}Sr contamination to the environment,
- the exposed shoreline and sediments of White Oak Lake, particularly secluded areas that are attractive to deer and where, based on historical data[16], ^{90}Sr contamination in native vegetation is expected to range between 100 and 1000 pCi/g,
- floodplains adjacent to White Oak Creek and Melton Branch where environmental ^{90}Sr contamination is suspected to exist because of prior events in the history of ORNL, or ^{90}Sr migration away from seeps

associated with solid waste storage areas.

To aid this identification process, unpublished data on ^{90}Sr concentrations in surface soil and grass from an area of low-level contamination bordering White Oak Creek are presented in Appendix B. Research is needed to empirically determine the plant:soil concentration ratios for ^{90}Sr in a variety of vegetation types from the White Oak Creek Watershed, so that sites requiring remedial actions can be confidently identified on the basis of ^{90}Sr levels in soils when plants are not present.

4. Model calculations suggest that if 30 pCi of ^{90}Sr per gram of deer bone is to be the accepted screening level for retaining deer killed on the reservation, then 5 pCi of ^{90}Sr per gram dry weight vegetation should be considered as a possible action level in making decisions about the need for remedial measures. This level is ~25 times the background ^{90}Sr concentration in plants that originates from weapons testing fallout. Theoretical calculations show that unrestricted access and 100% utilization of vegetation contaminated with <5 pCi of ^{90}Sr per gram dry weight (by a 45-kg buck) results in calculated steady-state (maximum) concentrations of <30 pCi/g in deer bone.

5. Remedial action in identified areas will likely require a combination of measures to minimize the food chain transport of ^{90}Sr to deer. Minimization measures might include deer exclusion, exclusion of vegetation, soil removal, soil treatment, and habitat modification, in combination with regular surveillance. Fencing to exclude deer or deep rock covers to prevent vegetation growth are possible low-cost measures for small (point-source) areas of ^{90}Sr contamination associated with seeps.

Research is needed on land management practices, such as habitat modification or soil treatments, that might be effective in deterring deer from contaminated areas or reducing the plant uptake of ^{90}Sr; it may be too expensive or difficult to remove contamination or to exclude deer by fencing larger (nonpoint-source) areas of low-level contamination.

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Appendix A
Strontium-90 Concentrations in Plant Samples

Table A.1. Concentrations of ^{90}Sr in plant samples from grid positions at the various seeps and corresponding GM ground-survey meter readings.

Seepage location	Grid location	Plant	Sample (g DW)	^{90}Sr (nCi/g DW)	GM meter (k cpm)
Bathtub seeps	D1	Fescue	0.38	0.80	0.5
	D2	Fescue	0.32	1.43	14.0
	D3	Fescue	0.44	1.79	9.0
	D4	Fescue	0.47	1.96	15.0
	D5	Fescue	0.43	0.81	18.0
	D6	Fescue	0.41	0.68	14.0
	D7	Fescue	0.43	0.47	1.2
	D8	Fescue	0.52	0.03	0.2
South of SWSA-4	D3	Honeysuckle	0.34	2.07	2.0
	D4	Grass/Sedge	0.17	0.65	2.2
	D5	Honeysuckle	0.40	1.70	1.0
	F4	Honeysuckle	0.36	7.11	0.9
	A4	Honeysuckle	0.35	3.24	2.2
	D8	Blackberry	0.27	9.17	2.2
	D9	Blackberry	0.39	12.61	2.6
	D10	Honeysuckle	0.48	20.70	2.2
	F9	Honeysuckle	0.42	11.62	2.5
	A9	Honeysuckle	0.33	5.17	2.3
Seep S-11 (SWSA-5)	B6	Honeysuckle	0.58	17.58	2.7
	C6	Honeysuckle	0.54	63.92	20.0
	D6	Honeysuckle	0.28	51.17	20.0
	E6	Honeysuckle	0.38	63.24	19.0
	B4	Honeysuckle	0.42	5.98	11.0
	B5	Honeysuckle	0.51	90.07	33.0
	C7	Honeysuckle	0.51	8.97	18.0
	D7	Honeysuckle	0.38	12.13	7.0
Seep S-5 (SWSA-5)	A1	Honeysuckle	0.40	20.82	15.0
	B1	Honeysuckle	0.41	71.60	18.0
	C1	Honeysuckle	0.35	31.05	31.0
	D1	Honeysuckle	0.36	6.24	8.0
	C2	Honeysuckle	0.39	3.80	12.0
	D2	Honeysuckle	0.37	4.07	4.0
	D3	Honeysuckle	0.24	2.40	2.0
	F5	Honeysuckle	0.35	10.40	23.0

Appendix B

Strontium-90 Concentrations in Soils and Vegetation from the White Oak Creek Floodplain

The White Oak Creek floodplain lies to the east of SWSA-4 (Fig. B.1) and borders an abandoned channel of White Oak Creek. A 30 x 30-m grid has been surveyed on the the floodplain, in conjunction with prior radioecology investigations[1], to study radionuclide migration from SWSA-4. The site, ~0.5 km downstream from ORNL, received effluents containing fission products when in service as a temporary settling basin during 6 months in 1944. The soil profile is azonal because of periodic erosion and deposition of sediments related to flooding. The soil texture is a loamy clay, and the soil is slightly alkaline (pH 7.1 to 7.6) because of alkaline treatment of the waste effluents in 1944. More detailed descriptions of this site, including maps of ^{137}Cs and ^{239}Pu contamination, can be found in references 1 through 3.

Paired samples of surface soil (0 - 7 cm) and plants were collected on the floodplain at 27 stations (Fig. B.2) in 1983. The mean surface soil ^{90}Sr concentration was 388 dpm/g DW. Plant samples, collected in June and August, were comprised principally of unidentified grasses and honeysuckle. The mean plant ^{90}Sr concentration was 608 and 375 dpm/g DW in June and August, respectively. Mean ^{90}Sr concentrations in plants were approximately equal to or 1.5 times greater than the mean concentration in surface soil (Table B.1). Two properties of the site that probably help to diminish the plant uptake of ^{90}Sr are the high (72%) silt content of the soil and the high soil pH. Nonetheless, ^{90}Sr concentrations in plants, over the ~9000-m^2 area surveyed in 1983, ranged from 129 to 1672 dpm/g DW (58 to 753 pCi/g DW) (Table B.1).

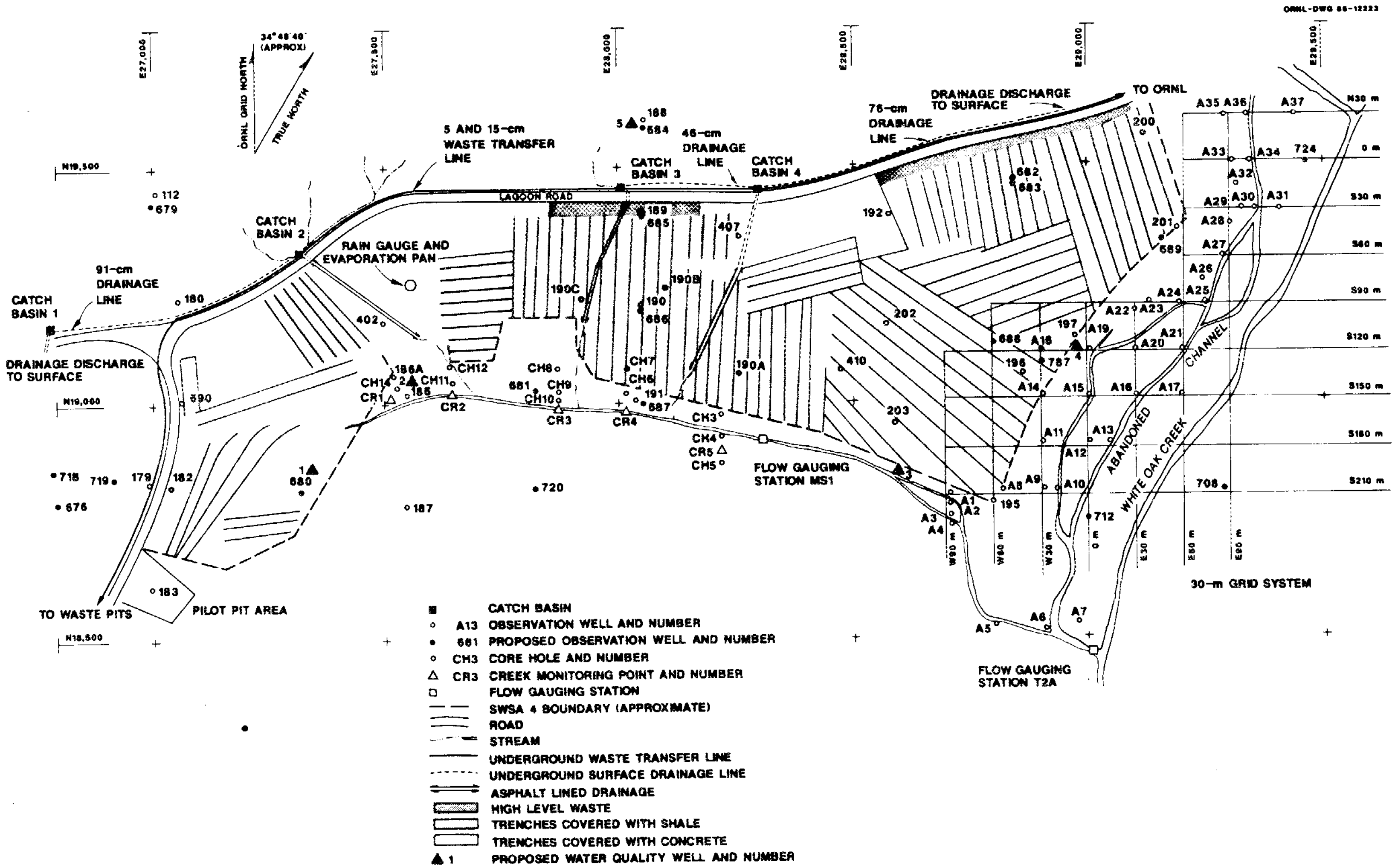

Fig. B.1. Map of SWSA-4 showing site features and location of the 30-m grid system superimposed on the White Oak Creek floodplain east of SWSA-4.

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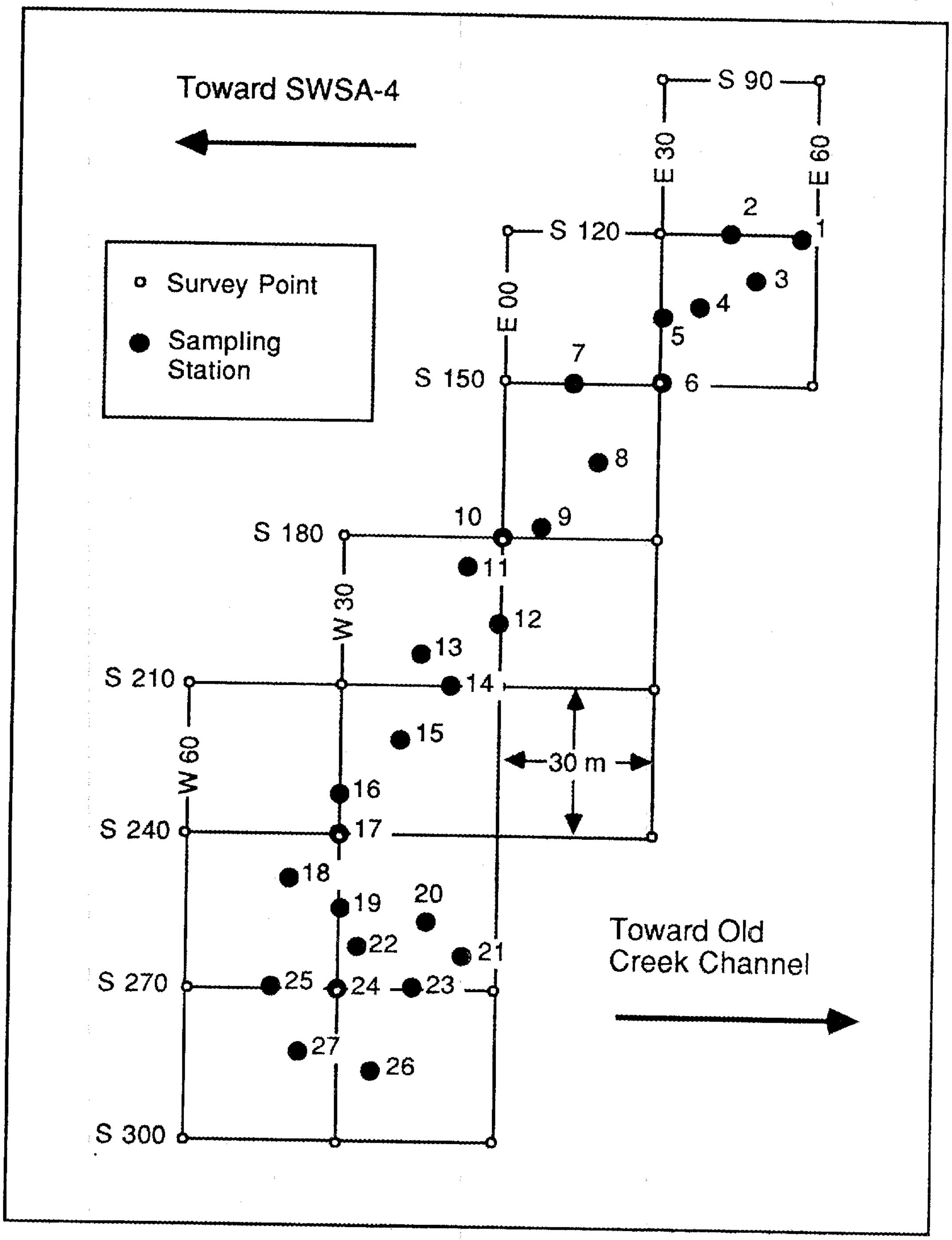

Fig. B.2. Sampling stations and grid survey points on the White Oak Creek floodplain east of SWSA-4.

Table B.1 Concentrations of ^{90}Sr in surface soils and plants and plant:soil concentration ratios from 27 locations on the White Oak Creek floodplain (1983)

Sample location[b]	^{90}Sr soil (dpm/g DW)[c]	Plant[a] ^{90}Sr concn. June (dpm/g DW)	Plant[a] ^{90}Sr concn. August (dpm/g DW)	Plant:soil concn. ratio June	Plant:soil concn. ratio August
1	766	438	766	0.57	1.00
2	258	330	230	1.28	0.89
3	272	210	178	0.77	0.65
4	438	462	437	1.05	1.00
5	319	444	269	1.39	0.84
6	389	420	433	1.08	1.11
7	644	895	314	1.39	0.49
8	230	326	152	1.41	0.66
9	302	524	228	1.74	0.76
10	452	448	298	0.99	0.66
11	256	448	297	1.75	1.16
12	269	471	129	1.75	0.48
13	274	551	302	2.01	1.10
14	282	437	272	1.55	0.96
15	329	959	349	2.92	1.06
16	350	708	278	2.02	0.79
17	292	454	305	1.56	1.05
18	443	915	445	2.06	1.00
19	279	618	246	2.21	0.88
20	300	233	257	0.78	0.86
21	246	194	219	0.79	0.89
22	550	743	1412	1.35	2.57
23	366	388	414	1.06	1.13
24	632	712	396	1.13	0.63
25	431	1651	326	3.83	0.76
26	505	754	508	1.49	1.01
27	607	1672	663	2.75	1.09
Minimum	230	194	129	0.57	0.48
Maximum	644	1672	1412	3.83	2.57
Mean	388	608	375	1.58	0.94
C.V.[d]	0.37	0.60	0.67	0.46	0.40

[a] Plant samples included mostly unidentified grasses with some minor inclusion of honeysuckle.
[b] Refer to Fig. B.2 for sample locations on surveyed grid.
[c] 2.22 dpm = 1 pCi.
[d] C. V. = coefficient of variation = mean / standard deviation.

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70. Robert L. Watters, Ecological Research Division, Office of Health and Environmental Research, Office of Energy Research, MS-E201, ER-75, Room F-226, U.S. Department of Energy, Washington, DC 20545
71. Leonard H. Weinstein, Program Director of Environmental Biology, Cornell University, Boyce Thompson Institute for Plant Research, Ithaca, NY 14853
72. F. W. Whicker, Department of Radiology and Radiation Biology, Colorado State University, Fort Collins, CO 80523
73. R. Wildung, Battelle Pacific Northwest Laboratories, P.O. Box 999, Richland, WA 99352
74. Raymond G. Wilhour, Chief, Air Pollution Effects Branch, Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency, 200 SW 35th Street, Corvallis, OR 97330
75. Frank J. Wobber, Division of Ecological Research, Office of Health and Environmental Research, Office of Energy Research, MS-E201, Department of Energy, Washington, DC 20545
76. M. Gordon Wolman, The Johns Hopkins University, Department of Geography and Environmental Engineering, Baltimore, MD 21218

77. Office of Assistant Manager for Energy Research and Development, Oak Ridge Operations, P. O. Box E, Department of Energy, Oak Ridge, TN 37831

78-107. Technical Information Center, Oak Ridge, TN 37831