Inventory of Radionuclides in Bottom Sediment of the Clinch River Eastern Tennessee

GEOLOGICAL SURVEY PROFESSIONAL PAPER 433-I

Prepared in cooperation with the U.S. Atomic Energy Commission and the Oak Ridge National Laboratory

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By P. H. CARRIGAN, JR.

TRANSPORT OF RADIONUCLIDES BY STREAMS

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INVENTORY OF RADIONUCLIDES IN BOTTOM SEDIMENT OF THE CLINCH RIVER EASTERN TENNESSEE

By P. H. CARRIGAN, JR.

ABSTRACT

An inventory has been made of the radionuclides associated with bottom sediment in the lower Clinch River. The reach included in this inventory extends 21 miles from the mouth of the river to the mouth of Whiteoak Creek.

The source of the radionuclides in the sediments was the release of low-level-radioactive waste waters from the Oak Ridge National Laboratory into Whiteoak Creek basin and thence into the river via Whiteoak Lake.

Results of the inventory indicate that the following quantities of radioactivity were associated with the bottom sediment in July 1962: 150 curies of cesium-137; 18 curies of cobalt-60; 16 curies of ruthenium-106; at least 10 curies of rare earths; and 2.9 curies of strontium-90. Most of the radioactivity was found to be downstream from mile 15; about 95 percent of the identified radioactivity was in this reach. Maximum concentration of radioactivity occurred near the mouth of Whiteoak Creek.

A high proportion of cesium-137 (21 percent), rare earths (about 25 percent), and cobalt-60 (9 percent) released to the river are retained in bottom sediment of the study reach. Retention of ruthenium-106 and strontium-90 is minor—less than 1 percent each.

INTRODUCTION

This report describes a contribution of the U.S. Geological Survey to the Clinch River Study. The Clinch River Study was a multiagency effort to evaluate the past, present, and future use of the Clinch River for disposal of low-level-radioactive liquid waste from the Oak Ridge National Laboratory, which is in eastern Tennessee (Morton, 1961, 1962b, 1963) and is operated by Union Carbide Corp. for the U.S. Atomic Energy Commission. The agencies that participated in the study are: Oak Ridge National Laboratory (ORNL); Tennessee Game and Fish Commission; Tennessee State Department of Public Health, Stream Pollution Control Board; Tennessee Valley Authority (TVA); U.S. Atomic Energy Commission (AEC); U.S. Geological Survey (USGS); and U.S. Public Health Service (PHS).

When the study was begun in 1960, the Clinch River Study Steering Committee, an advisory group composed of representatives of each of the participating agencies (Morton, 1963, p. 1) established the following objectives: (1) To determine the fate of radioactive materials currently being discharged to the Clinch River, (2) to determine and understand the mechanisms of dispersion of radionuclides released to the river, (3) to evaluate the direct and indirect hazards of current disposal practices in the river, (4) to evaluate the overall usefulness of the river for radioactive waste disposal purposes, (5) to provide appropriate conclusions regarding long-term monitoring procedures.

Work described in this report was part of a cooperative program with the Health Physics Division, ORNL; the Oak Ridge Operations Office, AEC; and the Division of Reactor Development and Technology, AEC.

The release of low-level-radioactive liquid waste to the basin of Whiteoak Creek, which drains the ORNL area, was begun soon after establishment of the Laboratory in 1943 for the processing of radioactive materials. Radioactive liquids have entered Whiteoak Creek as a result of direct releases of processed waste water from the Laboratory, seepage from liquid waste holdup pits, and drainage from solid-waste disposal trenches (Browder, 1959).

Throughout most of the Laboratory's history, the waters of Whiteoak Creek have been impounded in Whiteoak Lake by Whiteoak Dam, which is located 0.6 mile upstream from the mouth of the creek. The lake was created as a holdup facility for the radioactive waste carried in the creek water. Radioactive waste waters in Whiteoak Creek flow into the Clinch River at a point 3.3 miles downstream from the Laboratory area. The diluted wastes in the Clinch River flow into the Tennessee River 20.8 miles downstream from the entry of Whiteoak Creek.

The continuous release of radioactive wastes to the Clinch River during nearly 20 years of Laboratory operations has provided a unique opportunity for studying

the effects of such releases on the river and the effects of the physical, chemical, hydrologic, and biological characteristics of the river on the fate of the radioactive materials.

Since 1943 part of the radioactive materials released from ORNL through Whiteoak Dam (fig. 1) have become associated with bottom sediment of the Clinch River.

First indications of association of radionuclides with riverbed sediment came from work by Garner and Kochtitzky (1956). They made measurements, annually, of levels of radiation from the surface of the bottom sediment in the period 1951–53. Continued observation of annual changes in longitudinal distribution of radioactivity in surface layers of Clinch River bottom sediment by Cottrell (1959) suggested that accumulation of radioactive sediment might be occurring.

In 1960, coring of the Clinch River bottom sediment was undertaken at selected sites to explore more fully the possibility of accumulation of radioactive sediment. Variations in vertical distribution of radioactivity in a few cores strongly implied accumulation of radioactive deposits in the riverbed (Carrigan and others, (1967).

Partial inventory (upper strata) of radionuclides in Clinch River bottom sediment, derived from analysis of the 1960 cores, showed that retentions in the sediment of cobalt-60, rare earths, and cesium-137 probably

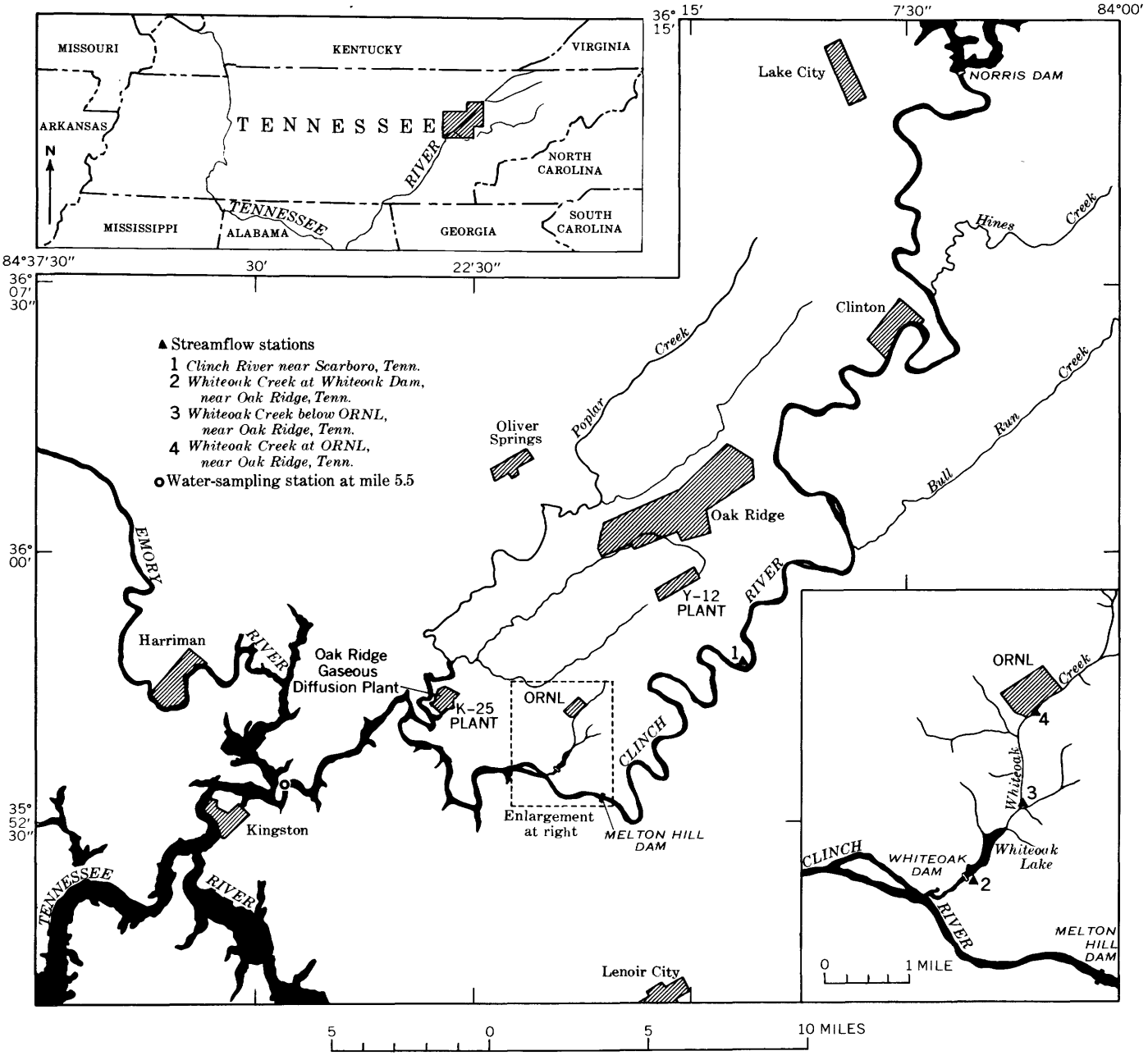

FIGURE 1.—Low-level-radioactive waste waters are released through Whiteoak Dam to the Clinch River, a tributary to the Tennessee River.

TABLE 1.—*Yearly discharges of radionuclides to the Clinch River*

[Results in curies. Results of total rare-earth (TRE) analysis include yttrium-90 content but exclude cerium-144 content. From Cowser and Snyder (1966, p. 6)]

Year	Gross beta	Cs^{137}	Ru^{106}	Sr^{90}	TRE	Ce^{144}	Zr^{95}	Nb^{95}	I^{131}	Co^{60}
1949	718	77	110	150	77	18	180	22	77	--------
1950	191	19	23	38	30	--------	15	42	19	--------
1951	101	20	18	29	11	--------	4.5	2.2	18	--------
1952	214	9.9	15	72	26	23	19	18	20	--------
1953	304	6.4	26	130	110	6.7	7.6	3.6	2.1	--------
1954	384	22	11	140	160	24	14	9.2	3.5	--------
1955	437	63	31	93	150	85	5.2	5.7	7.0	6.6
1956	582	170	29	100	140	59	12	15	3.5	46
1957	397	89	60	83	110	13	23	7.1	1.2	4.8
1958	544	55	42	150	240	30	6.0	6.0	8.2	8.7
1959	937	76	520	60	94	48	27	30	.5	77
1960	2,190	31	1,900	28	48	27	38	45	5.3	72
1961	2,230	15	2,000	22	24	4.2	20	70	3.7	31
1962	1,440	5.6	1,400	9.4	11	1.2	2.2	7.7	.36	14
1963	470	3.5	430	7.8	9.4	1.5	.34	.71	.44	14

ranged from 10 to 20 percent of the quantity released from ORNL (table 1; see Carrigan and others, 1967). A complete inventory could not be made because the coring tool did not completely penetrate the radioactive sediment (Morton, 1962a, p. 45–60).

Based on results of the partial inventory, the proportions of cobalt-60, rare earths, and cesium-137 releases associated with the river bed deposits in 1960 did not seem extraordinarily high. However, a complete inventory was needed to establish the quantity of radionuclides that had become associated with the bed deposits of the 21-mile-long study reach since 1943. Once the inventory was accomplished, the influence of the deposits on retention of these and other radioactive elements in the lower Clinch River would be better understood.

Information from the inventory of the radionuclides in Clinch River bottom sediment was obtained to meet the first objective of the Clinch River Study (see "Introduction"). Also, the information is applied to meet objectives 3, 4, and 5 of the study.

Data from this inventory may be applied to further refine safety analysis of current practices of radioactive waste disposal (third study objective; see Cowser and Snyder, 1966).

Estimates of the fraction of each radionuclide retained in the study reach may be used in forming a predictive model to evaluate the capacity of the Clinch River to safely receive radioactive liquid wastes (fourth study objective).

Techniques of collecting and analyzing samples, methods of ascertaining total quantity of radioactivity, and the accuracy of the inventory may suggest alternate or additional procedures that may be applied to long-term monitoring procedures (fifth study objective).

The bottom sediment was sampled by coring. Undisturbed cores were required in this inventory for use in measuring vertical distribution of the radioactivity in order to define the base of the radioactive zone throughout the study reach. Once the radioactive length of the core was determined, analyses for radionuclide content could be made, mass and volume of radioactive sediments could be computed, and the quantity of radionuclides in the sediments could be inventoried.

Cores were collected from preselected sections, extending from near the mouth of the Clinch River upstream to Melton Hill Dam (fig. 2).

The cores, collected in the summer of 1962, were also available for use in other studies. Pickering (1969) made use of them in investigation of vertical distribution of radioactivity and of physicochemical properties of the sediment.

ACKNOWLEDGMENTS

Inventory of radioactivity in Clinch River bottom sediment was financed by the Division of Reactor Development and Technology, AEC. A part of this financing was used for particle-size analysis at laboratories of the Water Resources Division, USGS, in Raleigh, N.C., and for a variety of services furnished through arrangements made by F. L. Parker, Health Physics Division, ORNL.

Services furnished at ORNL included a contract for coring with Sprague and Henwood, Inc., design and fabrication of the core scanner and the core saw, radiochemical analysis, use of a general purpose digital computer, laboratory technicians to assist in sample collection and in preparation of cores for physicochemical analysis, and consulting services.

Design and fabrication of the core scanner and core saw were by P. N. Hensley, Health Physics Division, and by C. D. Martin and W. F. Johnson, Instruments and Controls Division. Some radiochemical analyses were performed under the direction of C. L. Burros and J. H. Moneyhun, Analytical Chemistry Division. Advice in computer programing was given by M. T. Harkrider, R. P. Leinius, and A. M. Craig, Jr., Mathematics Division.

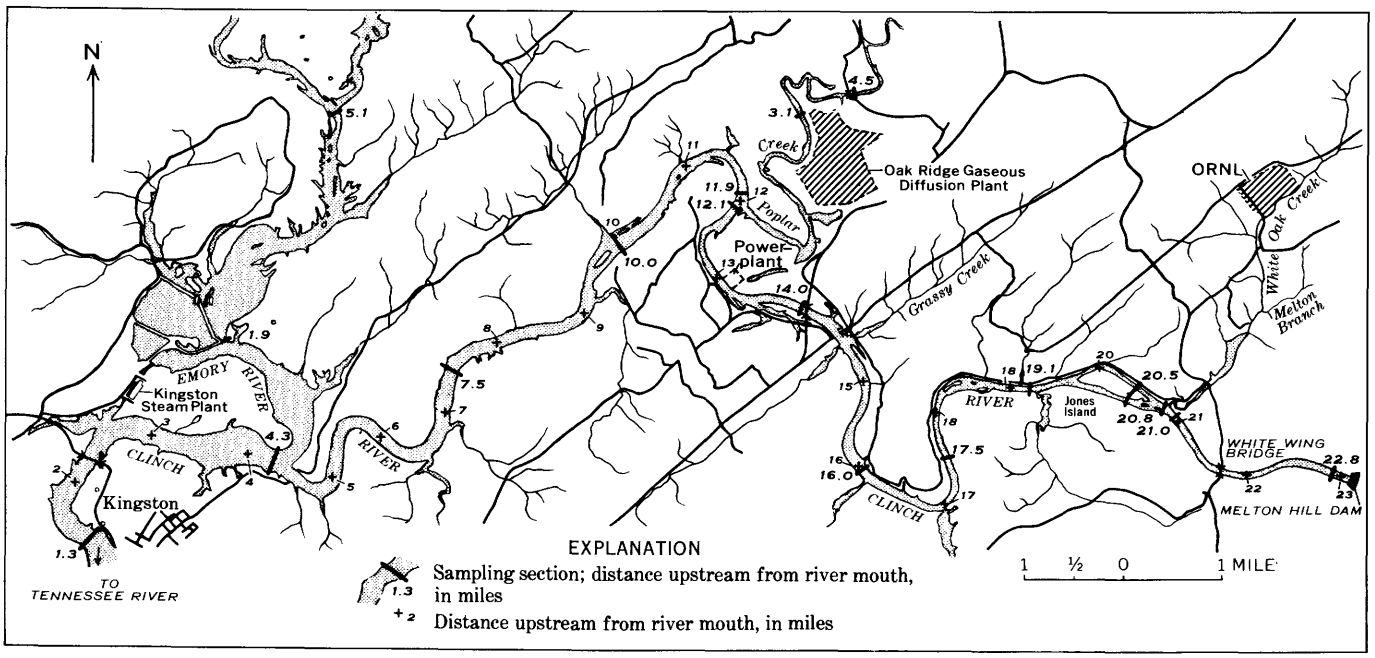

FIGURE 2.—Fourteen sampling sections were established in the Clinch River, downstream from Melton Hill Dam.

Persons making special contributions to this investigation were R. J. Pickering, USGS, who supervised coring operations and continually furnished valuable and timely advice; E. Schonfeld, Chemical Technology Division, ORNL, who made available the computer program for gamma spectrum analysis and supervised computer processing of gamma spectrum data; and E. R. Eastwood, Health Physics Division, ORNL, who was the major assistant in field and laboratory work.

Data on annual monitoring surveys of radioactivity in bottom sediment of the Clinch and Tennessee Rivers were furnished by H. H. Abee and W. D. Cottrell, Health Physics Division, ORNL; data on channel bed profiles at sediment ranges were furnished by J. W. Beverage, Chief, Hydraulic Data Branch, TVA.

Many illustrations in this report were prepared by Graphic Arts, ORNL.

CORING PROCEDURES AND RESULTS

Coring verticals were areally spaced to sample both variations in (1) distribution of radioactivity and (2) volume of bottom sediment in the study reach. In selection of sampling sites, longitudinal variations in radioactivity and in sediment volume and lateral variations in radioactivity were taken into consideration. Little was known of the thickness of the radioactive sediment. Therefore, the coring tool was driven to the maximum depth possible with the equipment used; generally this depth was at the top of bedrock or at the top of impenetrable soil lying below the sediment.

SELECTION OF SAMPLING SITES

Locations of sampling sections were based on the longitudinal pattern of radionuclide distribution in the study reach. Sections were selected to sample reaches of high and low radioactivity, locations at which breaks in the general trend of increasing or decreasing radioactivity occurred, and reaches of transition from one radiation level to another. Superposition of section location (fig. 2) on the longitudinal distribution pattern of radioactivity (Carrigan and others, 1967, p. 24) in figure 3 illustrates the relationship of location to variation in radioactivity.

The two sections established on the Emory River and on Poplar Creek (fig. 2) provided subsidiary information to health physicists at ORNL on possible upstream

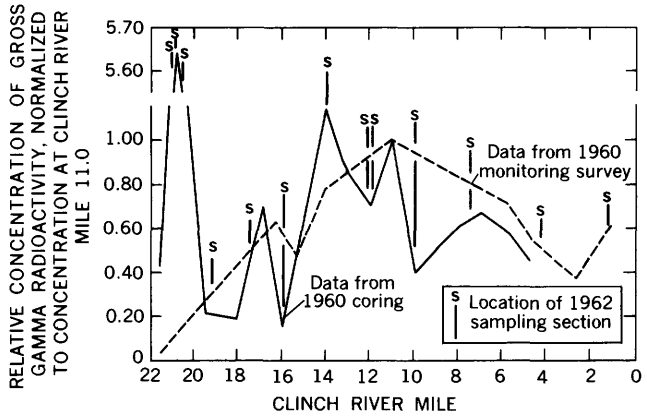

FIGURE 3.—Sampling sections were located in reaches of high, low, and transitional levels of radioactivity.

movement of radioactive contaminants into streams tributary to the Clinch River.

Spacing of coring verticals within a sampling section was chosen by combined assessment of transverse distribution of sediment thickness and of radiation levels at the sediment surface. Relation of spacing of verticals to variations in these variables for one sampling section is shown in figure 4.

CORING TOOLS

The author and his associate, R. J. Pickering, USGS, selected the Swedish Foil Sampler as the primary sampling tool after having made inquiries to other investigators engaged in sampling of bottom sediments, particularly marine sediments, and after having searched the literature on coring equipment.

Within the barrel of the Swedish Foil Sampler (fig. 5) are 16 steel foils (0.05 inch wide by 0.0005 inch thick) which completely line the barrel. The foils prevent friction between the sediment core and the walls of the barrel; as the sampler is pushed into the sediment, the foils unroll from coils stored in a magazine in the head of the sampler. Foils are pulled from the magazine because one end is affixed to a piston within the barrel; the vertical position of the piston is fixed at, or just above, the sediment surface as the head and barrel of the sampler are pushed into the sediment.

Little or no compaction of sample apparently occurred in the use of the Swedish Foil Sampler. Recovery of cores was very satisfactory, especially if a basket shoe and a plastic sleeve were inserted as retainers in the sampler tip.

A more complete description of the sampler, its use, and results of its application is given by Pickering (1965).

The Swedish Foil Sampler could not be used in soupy sediments, in sandy sediments, and in sediments consisting mostly of pebbles and gravel. For soupy sediments, SCUBA divers drove a thin-walled, 2½-inch coring tube into the sediment. For sandy sediments, sampling was done with a split-barrel sampler, containing a basket shoe and a plastic sleeve for sample retention. Hand-operated clam-shell dredges were used to collect gravel samples.

RESULTS OF CORING

In the summer of 1962, cores were collected at 135 verticals in 14 sections in the Clinch River and in 4 sections in tributaries to the river (see fig. 2). The number of verticals in a section ranged from 4 to 13.

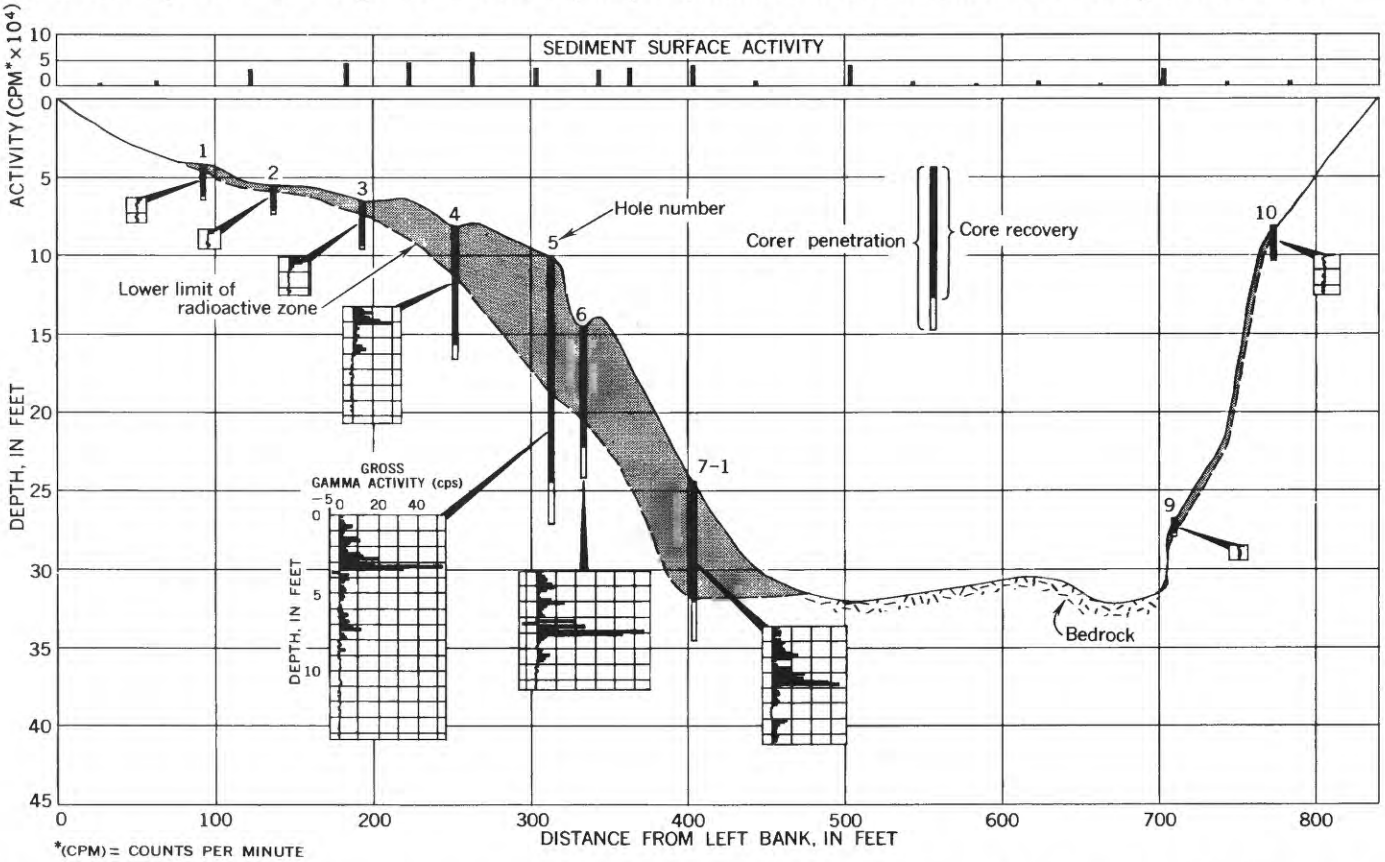

FIGURE 4.—Coring-tool penetration, sample recovery, transverse distribution of sediment thickness and of surface radiation levels, and vertical distribution of gross gamma radioactivity at Clinch River mile 7.5 (from Pickering, 1969).

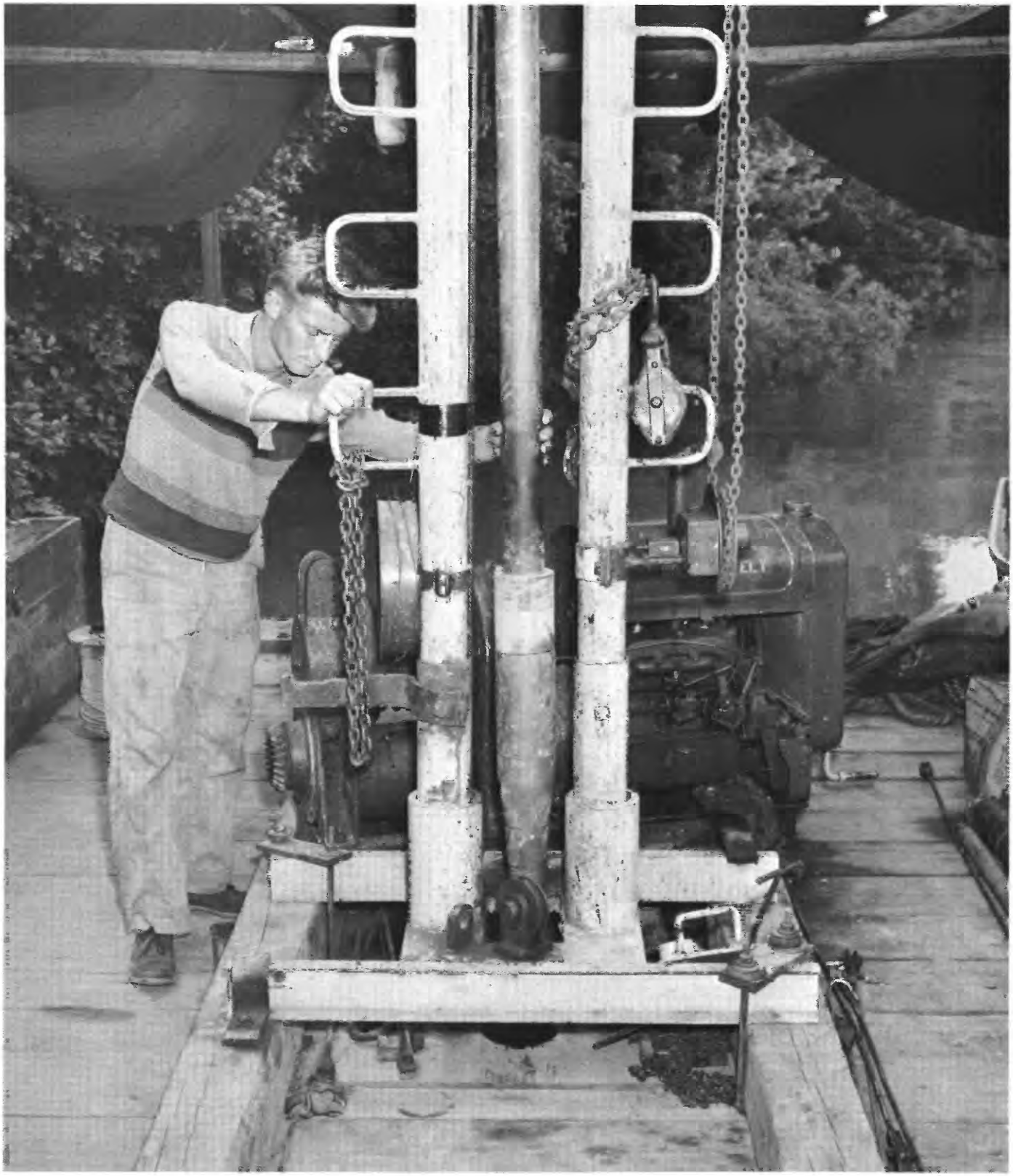

FIGURE 5.—Coring was done from a barrel float. Sampler head and part of the segmented barrel of the Swedish Foil Sampler are suspended from drilling tower.

Relationships between depth of penetration, length of core recovered, and thickness of the radioactive zone at CRM (Clinch River mile) 7.5, seen in figure 4, exemplify the success of coring operations generally experienced throughout the study reach. The abbreviation CRM followed by a number has been used in this report to designate distance, in miles, upstream from the mouth of the river. This terminology is consistent with prior usage in the Clinch River Study (Morton, 1961) .

Results of coring at each section are summarized in table 2. Two situations of special significance to the summary of coring results are emphasized by the table: (1) 15 cores did not completely penetrate the radioactive zone, and (2) not all cores or dredge samples were found to contain significant quantities of radioactivity in subsequent analyses. Therefore, samples containing no radioactivity were excluded from further direct consideration in computations.

TABLE 2.—*Numbers of sampling sites, of samples used in computations, and of truncated cores used in computations for each sampling section*

[Length of truncated core recovered is less than thickness of radioactive zone]

Location of sampling section (miles upstream from mouth)	Coring verticals	Dredge samples	Used in computations		
			Cores	Dredge samples	Truncated cores
Clinch River					
1.3	10	0	8	0	3
4.3	13	0	12	0	3
7.5	9	0	9	0	1
10.0	11	0	10	0	2
11.9	11	0	10	0	1
12.1	11	0	11	0	3
14.0	5	0	5	0	0
16.0	7	0	7	0	0
17.5	6	0	6	0	0
19.2	5	0	4	0	0
20.5	8	6	8	6	1
20.8 [1]	5	7	3	7	1
21.0	4	0	2	0	0
22.8	5	1	5	1	0
Emory River					
1.9	7	0	5	0	0
5.1	7	0	0	0	0
Poplar Creek					
3.1	5	0	0	0	0
4.5	6	0	0	0	0

[1] Section 100 feet downstream from mouth of Whiteoak Creek.

CORE PROCESSING

Core processing was divided into four major procedures: measurement of gross gamma radiation distribution, longitudinal cutting, preparation of composite samples for analyses, and physical and radiochemical analyses of composites. Until the final two processing procedures were undertaken, the cores (and dredge samples) were frozen.

Cores were frozen shortly after collection for two reasons: (1) To suppress biological and chemical action and (2) to prevent distortion of the plastic cohesive samples.

The frozen cores, still wrapped in steel foil and encased in a plastic tube, were placed in a specially fabricated radiation-counting apparatus called a core scanner (fig. 6). The core scanner was used to automatically measure the gross gamma radiation in 2-inch increments along the full length of the core. For measurement of distribution of gross gamma radiation, the electrical output from the photomultiplier tube was routed to a scaler (Pickering, 1969).

Limitation of radiation detection to a 2-inch increment was improved by inclusion of a collimated detector in the core scanner. However, the length of the collimator channel (2-in.) was too short for precise collimation, and radiation from zones of core above and below the face of the collimator was detected. Through calibration of the instrument, effects of imperfect collimation on radiation measurements were corrected.

For accuracy and economy, the corrections due to imperfect collimation were applied to the counting data from the scaler by means of a computer program. Examples of the bar-graph plots, derived from the computer program and showing radiation distribution for 2-inch incremental lengths of core, are given in figure 4.

Corrected counting data for each 2-inch-high slice of core were used to define the thickness of the radioactive zone at each core vertical (see fig. 4). These data were also used as a guide in determining cores in which there was no significant radioactivity.

After the counting of gross gamma radiation, each core was cut longitudinally into halves and one of the halves was divided longitudinally to provide a quarter-section sample for use in the inventory and to provide duplicate samples for use by Pickering (1969) in his studies of vertical distribution of radioactivity and the physicochemical characteristics of the sediments. Cutting was done by placing the frozen core in a jig and passing the jig through a carbide-tipped circular saw (fig. 7). The quarter-section core cylinders used in this inventory were cut horizontally at the base of the radioactive zone, and the nonradioactive part was discarded.

After cutting, the volume and weight of the cylinder of radioactive sediment were measured for determination of specific bulk weight. The volume of the cylinder (including void space) was found by permitting the frozen material to melt in a calibrated vessel. For these volumetric measurements, voids in the sediment were assumed to be completely filled with water.

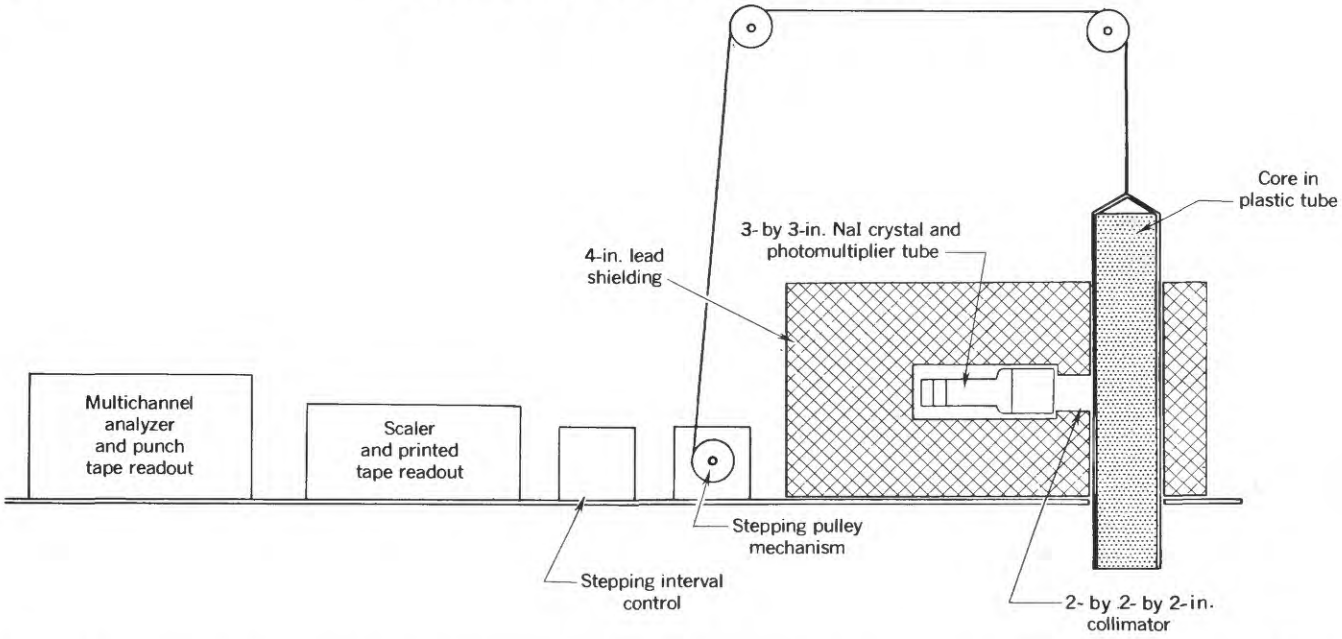

FIGURE 6.—Core is hoisted through well in core scanner for detection of gamma radiation. Electric output from photomultiplier of detector may be routed to scaler or analyzer (from Pickering, 1969).

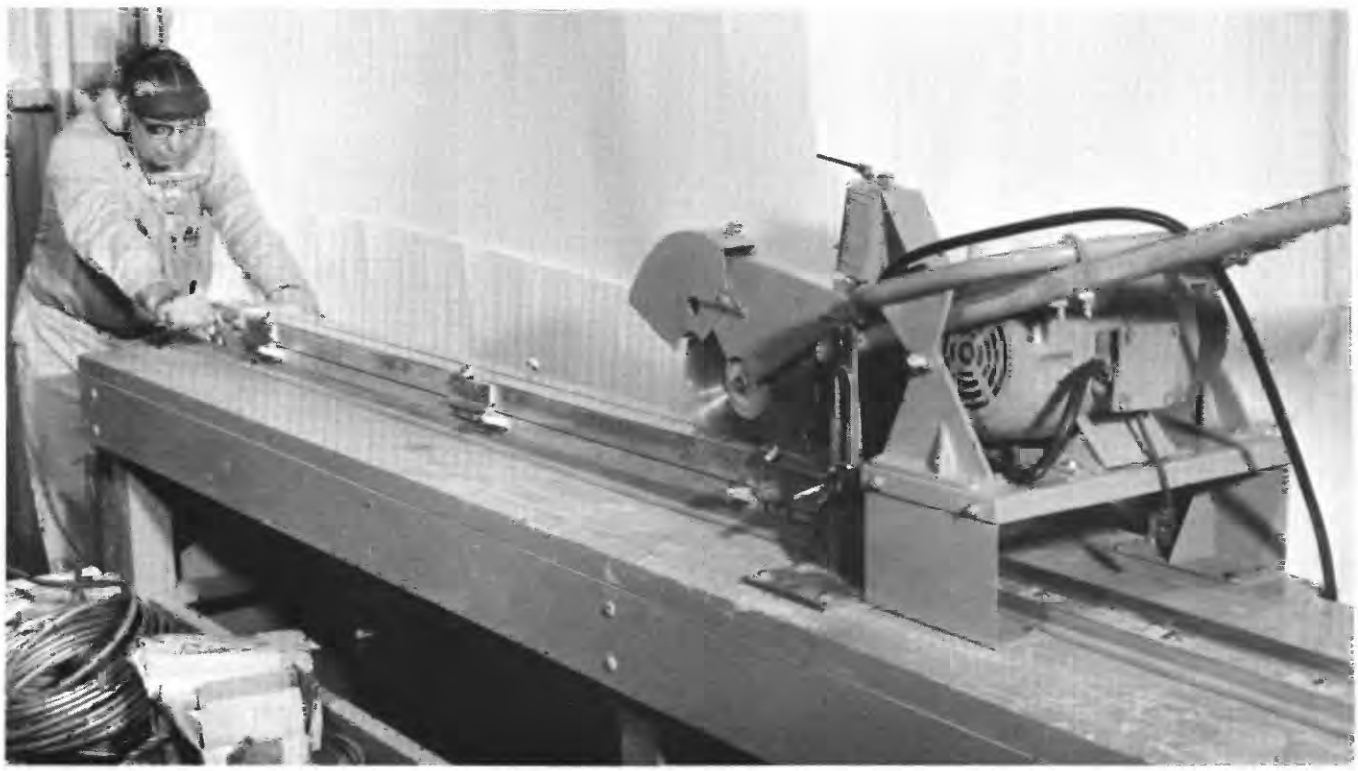

FIGURE 7.—A masonry saw was modified to cut frozen cores. Jig holding core rolled under saw blade between guides on table.

Next, a homogeneous composite of the quarter-section cylinder was prepared by using an electrically driven eggbeater. Preliminary tests showed that sediments ranging from highly cohesive to noncohesive could be homogeneously mixed in 10 minutes.

A 1-gram aliquot was split from the composite for analysis of particle-size distribution at laboratories of the USGS in Raleigh, N.C. Then, the remaining composite was weighed, dried at 100° C (Celsius), and reweighed to provide data for computation of the dry-to-wet weight ratio of the composite.

The dry composite was split into aliquots for radiochemical analyses using a Jones soil splitter. A 100-gram aliquot (±0.01g) was prepared for gamma spectrum analysis, and a 20–50 gram aliquot was prepared for analyses of strontium-90 and trivalent rare-earth contents.

Radiochemical analyses for strontium-90 and trivalent rare-earth contents of the 20–50 gram aliquots were performed at the Low-Level Counting Facility, Analytical Chemistry Division, ORNL. Standard methods of chemical extraction of the specified elements and beta counting of the extracts were used in these analyses (Raaen and Cline, 1964).

Analysis of concentrations of cesium-137, cobalt-60, and ruthenium-106 in composites of the bottom sediment was made by techniques of gamma spectrometry by using a sodium iodide crystal, 4 inches high by 4 inches in diameter, for a detector and by using a 512-channel pulse-height analyzer. Derivation of concentrations for the desired radionuclides from punch-taped data was obtained by means of a computer program which utilized a technique of least-squares resolution of the gamma-ray spectra (Schonfeld and others, 1965). Input data for the computer program included the spectra for the sample, the background associated with the sample, and known concentrations of selected radionuclides (standards). Standards were selected on the basis of records of releases of radionuclides from Whiteoak Lake, experience from other investigations of radioactivity in bottom sediments (see Cottrell, 1959; Carrigan and others, 1967), and the knowledge that naturally occurring radionuclides are found in soil and rock of the area. Standards included were cesium-137, cobalt-60, ruthenium-106, cerium-144, zirconium-95, niobium-95, cesium-134, europium-152, europium-154, potassium-40, uranium ore, and thorium ore.

To assure that results of radionuclide analyses by gamma spectrometry were reasonably accurate, nine selected samples were reanalyzed at the Low-Level Counting Facility, ORNL. These samples were selected as representative of the general range of radioactivity and of sampling location for samples collected throughout the study reach. Analysts at this facility found that concentrations of only two radioactive contaminants, cesium-137 and cobalt-60, could be reliably determined by their method of hand computation of gamma spectra data produced from their pulse-height analyzer. Results for concentrations of cobalt-60 and cesium-137 determined by these analysts were slightly greater than those determined by computer program—7.8 and 13.8 percent greater, respectively.

Differences in results between computer and hand processing of counting data are believed logical; but the computer-derived concentrations are considered to be most accurate. Methods of hand computation do not appear to be sufficiently sensitive and precise to detect, or to compensate for, the presence of minor constituents in a sample if the concentrations of these constituents are 100 or more times less than concentrations of major constituents.

Cores presumptively containing no radioactivity—based on results of gross gamma core scanning—were reevaluated by careful examination of results of gamma spectra analyses for cesium-137 and cobalt-60 contents. Cores which contained concentrations of these radionuclides slightly greater than limits of detection were included in the inventory.

COMPUTATION OF INVENTORY

The volume of radioactive sediments is divided into subvolumes when computing the inventory. The quantity of a radionuclide in a subvolume is equal to the product of its concentration (curies per unit weight) and weight of sediment in the subvolume. Total quantity of the radionuclide in the study reach is the sum of its quantities in the subvolumes.

Locations of sampling sections and of coring verticals in the study reach serve as controls for dividing the volume of sediment into subvolumes. Each subvolume is associated with a specific coring vertical.

Shape of each subvolume is assumed to be prismatic; its length extends from midpoints between adjacent sampling sections; its width extends from midpoints between adjacent coring verticals in the sampling section; and its depth is equal to the thickness of the radioactive zone for the specified core. These definitions of dimensions of a subvolume are modified for the two terminal subreaches and for terminal verticals (where thickness of sediment is zero) in a sampling section.

The length of the terminal subreach for subvolumes associated with the sampling section at CRM 1.3 extends from CRM 0.0 to the midpoint between CRM 1.3 and 4.3. The length of the terminal subreach for subvolumes associated with the sampling section at CRM 21.0 extends from the midpoint between CRM 20.8 and 21.0 to

CRM 21.0. The widths of radioactive zones in the sampling sections did not extend in every case from one edge of water to the other. Hence the transverse locations of at least two, and sometimes more, terminal verticals of radioactive zone(s) in a section had to be defined. These terminal verticals were defined on the basis of (1) locations of cores that contained no detectable radioactivity, (2) rates of change of the gamma radiation levels at the surface of the bottom sediment, (3) rates of change in thickness of the radioactive zone, (4) transverse slope of the streambed, and (5) limits of bedrock areas as determined by probing of the bed material. The influence of some of these factors on location of terminal verticals is indicated in figure 4.

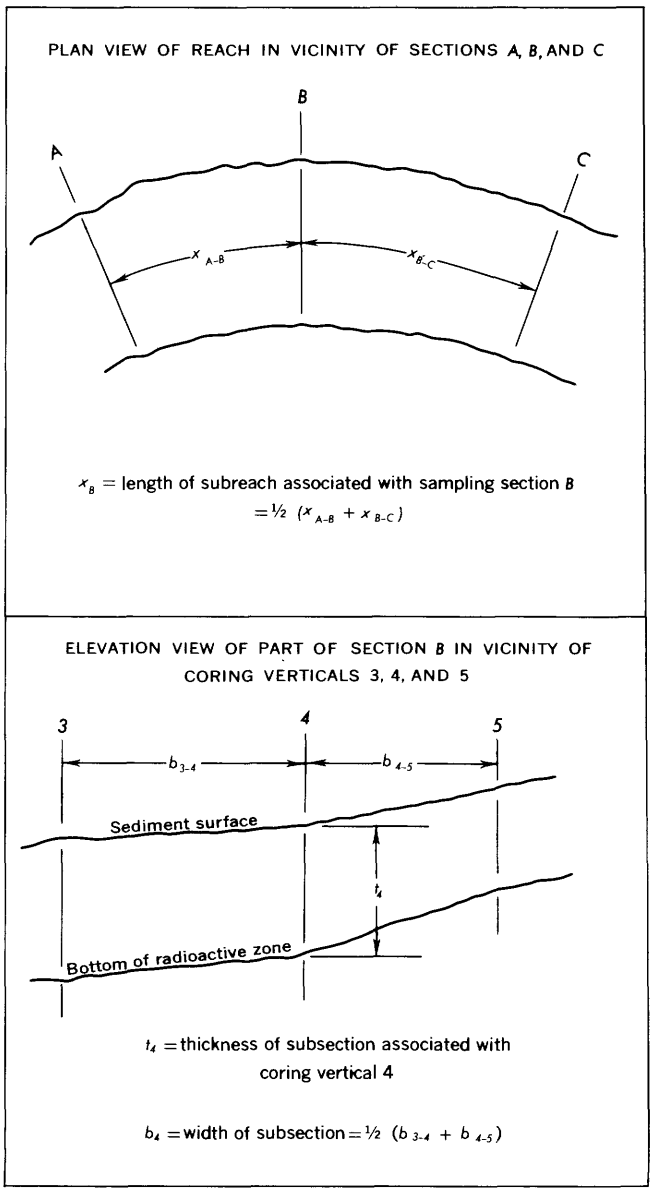

FIGURE 8.—Methods of determining length, width, and thickness of subvolumes.

The width of the subvolume associated with a coring vertical adjacent to a terminal vertical was computed in the same manner as widths of other subvolumes.

A diagram of the methods of determining length, width, and thickness of subvolumes is shown in figure 8.

Sediment weight in a subvolume is the product of its volume and of the specific bulk weight and dry-to-wet weight ratio of its associated core. Specific bulk weight is the wet weight per unit volume. Equations for computations are as follows:

$$V_s = xbt$$

in which V_s = volume of subvolume in cubic meters,

x = length of subreach in meters,
b = width of subvolume in meters, and
t = thickness of radioactive zone in meters.

$$V = \Sigma V_s$$

in which V = total volume of radioactive sediment in study reach in cubic meters.

$$W_s = V_s s \frac{w_d}{w_w}$$

in which W_s = weight of sediment in subvolume in grams, ovendry basis,

s = specific bulk weight in grams per cubic meter, wet-weight basis, and

$\frac{w_d}{w_w}$ = dry-to-wet weight ratio.

$$R_s = CW_s$$

in which R_s = quantity of radionuclide in subvolume in picocuries (10^{-12} curies),

C = concentration of radionuclide in composite in picocuries per gram, ovendry basis.

$$C_x = \frac{\Sigma R_s}{\Sigma W_s}$$

in which C_x = mean concentration of radionuclide in sampling section in picocuries per gram.

$$R = \Sigma R_s$$

in which R = total quantity of radionuclide in study reach in picocuries.

$$t_x = \frac{\Sigma V_s}{B}$$

in which t_x = average thickness of radioactive sediment at sampling section in meters.

B= total width of radioactive zone at sampling section in meters.

$$A_x = \Sigma bt$$

in which A_x= cross-sectional area of radioactive zone at sampling section in square meters.

Computations using these equations were facilitated through use of a general purpose digital computer. All dimensional units were converted to those commonly used in American engineering practice for presentation of results.

As shown in table 2, the recovered length of some cores was less than the thickness of the radioactive zone; these cores are termed truncated. Thicknesses of radioactive sediment for truncated cores and dredge samples were estimated as follows: Distribution patterns of gross gamma radiation were discernable in many truncated cores; patterns of radioactivity distribution in such cores were compared to patterns for cores which penetrated the entire radioactive zone at nearby coring verticals; comparisons were made using correlation analyses developed in study of vertical distribution of radioactivity (Pickering, 1969); from results of these comparisons, the depth to which radioactivity extended could be estimated for truncated cores.

In some instances the truncated length was too short to clearly discern the distribution pattern of radioactivity, in which case the radioactive thickness at the coring vertical was assumed to be equal to the depth of penetration of the coring tool. Fortunately, the fraction of core recovered was large in most cases.

The scope of the adjustment procedures is summarized in table 3.

TABLE 3.—*Method of estimating depth of radioactivity of truncated cores collected in the Clinch River*

[Length of truncated core recovered is less than thickness of radioactive zone]

Location of sampling section (miles upstream from mouth)	Number of cores adjusted through correlation [1]	Adjustment based on depth of coring-tool penetration	
		Number of cores	Length of ratio [2]
1.3	2	1	0. 75
4.3		3	0. 67, 0. 74, 0. 82
7.5	1		
10.0	2		
11.9	1		
12.1	1	2	0. 42, 0. 68
20.5		1	0. 50
20.8		1	0. 73

[1] Adapted from results of work by Pickering (1969).
[2] Ratio of truncated length to depth of penetration (radioactive length).

Approximately 2 years elapsed between collection and radiochemical analyses of cores. During this period, decrease in radioactive content through the process of radioactive decay was appreciable for some radionuclides. Concentrations used in the computations were adjusted to those at the time of sampling, except for rare earths. No adjustment for radioactive decay of rare earths was made because they are a mixture of radionuclides having a variety of radioactive half lives. Methods of adjustment for effects of radioactive decay on radiation have been described by the U.S. Public Health Service (1960).

Depth of penetration of hand-operated dredges could not be measured. Depths were computed by using information on volume of sample collected and on geometric characteristics of the sampler. Computed depth of sampling was assumed to be the radioactive depth.

RESULTS

In the course of acquiring necessary data to inventory radioactivity in Clinch River bottom sediment, information has been gathered not only on quantities of radionuclides in the sediment but also on distribution of radionuclides in these sediments and distribution of the sediments in the river.

INVENTORY OF IDENTIFIED RADIONUCLIDES

The following quantities of radionuclides are associated with bottom sediments of the Clinch River between CRM 0.0 and 21.0: 150 curies of cesium-137, 18 curies of cobalt-60, 16 curies of ruthenium-106, at least 10 curies of rare earths, and 2.9 curies of strontium-90.

All quantities have been adjusted for effects of radioactive decay to those quantities present at the time of sampling (July 1962), except for the rare earths (see "Computation of inventory"). Quantity of rare earths reported is that present at the time of radiochemical analysis.

Total inventoried and identified radioactivity is 200 curies, of which cesium-137 constitutes 77 percent; cobalt-60, 8.7 percent; ruthenium-106, 7.7 percent; rare earths, 5.1 percent; and strontium-90, 1.5 percent.

About 95 percent of the identified radioactivity is in the reach of river downstream from CRM 15 (table 4). At least 50 percent of the identified radioactivity is downstream from CRM 8.7.

ESTIMATE OF ACCURACY OF INVENTORY

The quantity of a radionuclide in a volume of sediment, R, may be expressed by the equation

$$R = Cxbts\frac{w_d}{w_w},$$

in which the independent variables are, respectively, concentration of a radionuclide, length of subreach, width of sampling section, mean thickness of radioactive sediment in sampling section, specific bulk weight, and dry-to-wet weight ratio. The following

expression is used to compute the level of expected error in R:

$$\sigma_R = R\sum_1^6 \frac{\sigma_Z}{Z},$$

in which σ_R is the standard deviation for R, σ_Z is the standard deviation for each independent variable Z, and $\frac{\sigma_Z}{Z}$ is the relative error, or coefficient of variation, for Z.

The relative error in the measurement of physical properties which appear in the above equation has been estimated by comparing the precision in measuring each property to the magnitude of the property. Errors in measuring specific bulk weight and dry-to-wet weight ratio are less than 5 and 2 percent, respectively. Relative errors in dimensions of sediment volume have been estimated for each subreach downstream from CRM 15. Limitation in considered reach length has been made because 95 percent of the radioactivity is downstream from CRM 15. Coefficients of variation for subreach length, width, and thickness are about 3, 5, and 15 percent, respectively. Other independent sources of error in the determination of radionuclide concentration are accuracy of radionuclide standards, counting errors in analysis, and sampling errors. Error in radionuclide content of standards is about 5 percent. Average levels of counting errors for cesium-137, cobalt-60, ruthenium-106, strontium-90, and rare earths are 2, 8, 23, 4, and 2 percent, respectively.

The estimated errors in inventory—sampling error being neglected and the foregoing expression for σ_R being used—are as follows: 18 percent for cesium-137, strontium-90, and rare earths; 20 percent for cobalt-60; and 29 percent for ruthenium-106.

TABLE 4.—*Quantity of total identified radioactivity and volume of radioactive sediment in subreaches*

Location of subreach		Total identified radioactivity, in curies		Volume, in acre-ft	
Begin	End	In subreach	Cumulative	In subreach	Cumulative
CRM 0	CRM 2.80	22	22	340	340
2.80	5.90	42	64	380	720
5.90	8.95	54	118	480	1,200
8.95	10.95	46	164	430	1,630
10.95	12.00	9	173	93	1,720
12.00	13.05	10	183	85	1,810
13.05	15.00	6.8	191	38	1,850
15.00	16.75	2.2	193	33	1,880
16.75	18.35	4.7	198	39	1,920
18.35	19.85	.1	198	4.7	1,920
19.85	20.65	2.3	200	5.9	1,930
20.65	20.90	.1	200	1.4	1,930
20.90	21.00	.2	200	.3	1,930

RETENTION FACTORS

The retention factor for a radionuclide is defined as the ratio, expressed in percent, of the quantity of the radionuclide in the sediment in July 1962 to that quantity released to the river during the period December 1943 to July 1962.

The magnitude of the retention factor is independent of time if radioactive decay is taken into account.

$$k_r = \frac{I-O}{I}(100) = \frac{R}{Ie^{-\lambda t}}(100),$$

$$I = \int_0^T i\,dt,$$

$$O = \int_0^T o\,dt,$$

in which k_r = retention factor, in percent,
I = inflow of radionuclide to study reach during time period T, in curies,
O = outflow of radionuclide from study reach during time period T, in curies,
R = quantity of radionuclide in bottom sediment of study reach at end of period T, in curies,
λ = radioactive decay constant for radionuclide, in seconds $^{-1}$,
T = duration of time period, in seconds,
i = rate of inflow of radionuclide to study reach, in curies per second, a function of time,
o = rate of outflow of radionuclide from study reach, in curies per second, a function of time, and
t = time, in seconds.

R may be expressed as a function of inflow and outflow if the effect of radioactive decay is considered.

$$R = \int_0^T ie^{-\lambda(T-t)}dt - \int_0^T oe^{-\lambda(T-t)}dt$$

$$= e^{-\lambda T}\int_0^T idt - e^{-\lambda T}\int_0^T odt$$

$$= e^{-\lambda T}(I-O)$$

Hence,

$$k_r = \frac{R}{Ie^{-\lambda T}}(100) = \frac{e^{-\lambda T}(I-O)}{e^{-\lambda T}I}(100) = \frac{I-O}{I}(100)$$

and is independent of time.

Only annual records of inflow are available so that it is necessary to use numerical techniques to compute k_r:

$$k_r=\frac{R_m/e^{-\lambda T_z}}{\sum_{n=1}^{T} i_n e^{-\lambda(T-n)}}(100),\ n=1, 2, \ldots, T \text{ years} \quad (1)$$

in which $R_m=Re^{-\lambda T_z}$=inventory of radionuclide at time of radiochemical analysis, in curies,
λ=radioactive decay constant, in years,
T_z=time between collection of cores and radiochemical analysis, in years, and
i_n=annual inflow of radionuclide to study reach during nth year, in curies per year.

Pickering (1969) had previously evaluated the dominator in equation 1.

Using equation 1, the retention factors are computed to be 21 percent for cesium-137, 9 percent for cobalt-60, 0.4 percent for ruthenium-106, and 0.2 percent for strontium-90. Retention of the rare earths may approach, and possibly may exceed, 25 percent (see Struxness and Morton, 1961). A good estimate of the retention factor for rare earths has not been obtained because mixtures of radioelements of undetermined composition are involved. The above estimate was derived from a conservative consideration of the cerium-144 and other rare-earths contents of three samples.

DISTRIBUTION OF RADIONUCLIDES

LONGITUDINAL DISTRIBUTION

Patterns of longitudinal variation in mean concentration of principal radionuclides (fig. 9) are similar in most respects. Highest mean concentrations of radionuclides are in the two sections immediately downstream from the mouth of Whiteoak Creek (CRM 20.8 and CRM 20.5). Lowest concentrations generally are in sediments of the next downstream sampling section at CRM 19.2. Secondary peaks in the distribution (fig. 9) occurred at CRM 17.5 and 14.0. Mean sectional concentrations for all but one radionuclide abruptly decreased between sections immediately upstream and downstream from the mouth of Poplar Creek (CRM 12.0).

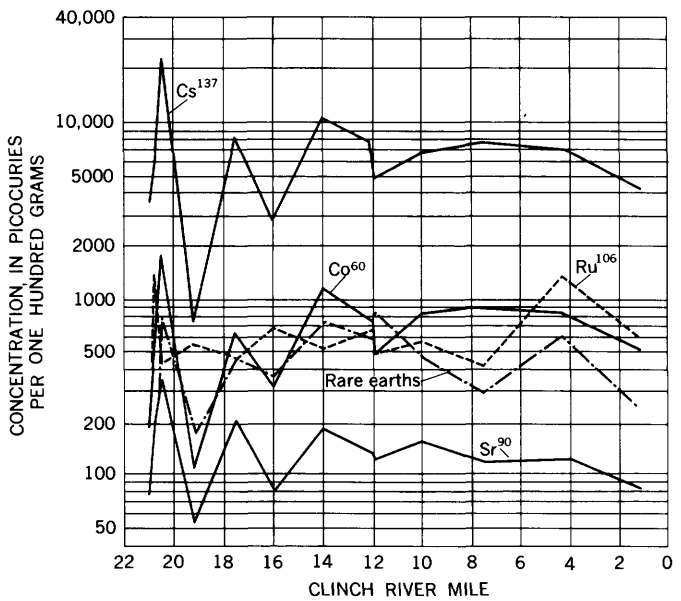

FIGURE 9.—Similarities in longitudinal distribution of radionuclides in bottom sediment are observed throughout study reach.

Distribution of radioactivity in Clinch River bottom sediment is controlled primarily by sedimentation (Carrigan and others, 1967; Pickering, 1969). Radionuclides in the bottom sediment become intimately associated with suspended sediments passing through Whiteoak Dam. Patterns of radioactive deposits in the river result from the combined interaction of lateral diffusion, characteristics of the flow pattern, and decreasing intensity, downstream, of turbulent forces acting to suspend the radioactive sediment particles from Whiteoak Creek. Therefore, similarities in concentration distribution are to be expected.

Investigation of the movement of sediments has not been a part of the Clinch River Study. As a consequence, careful documentation of the effects of diffusion, flow distribution, and turbulence on sedimentation is not available. However, the influence of these three on the longitudinal distribution may be surmised from observation and general understanding of mechanics of fluid motion.

High concentrations of radioactivity in bottom sediments may be expected near the mouth of Whiteoak Creek. Dispersion of waters and suspended sediments from the creek into the river is restricted because of incomplete lateral diffusion (Morton, 1962b and 1963; Carrigan and others, 1967). Consequently, suspended sediments from Whiteoak Creek, which are rich in sorbed radioactivity, do not immediately become diluted with relatively uncontaminated river sediments.

Abrupt changes in the momentum of the water entering the river from the creek tend to induce deposition. Eddy zones along the right bank of the river immediately downstream from the creek mouth are created as the two streams meet. The eddies and the restricted dispersion of sediments produce immediate concentrated deposition of suspended sediments rich in sorbed radioactivity.

Suspended sediments from the creek diffuse outward into the river channel and mix with sediments carried in the river. This action prevents the formation of additional pockets of deposited sediments containing high concentrations of radioactivity.

Turbulence is of sufficient intensity in the upstream

part of the study reach to keep sediments in suspension through reaches such as those near CRM 19.2.

The abrupt decrease in concentration of radionuclides in bottom sediment in the downstream direction at the mouth of Poplar Creek may be the result of dilution of contaminated river sediments by uncontaminated sediments from Poplar Creek.

About the time cores were collected for use in this inventory, the annual monitoring survey of radioactivity in Clinch River bottom sediment was being conducted by personnel of the Applied Health Physics Section, ORNL. In the monitoring surveys, attempts are made to collect samples of the upper part of the bottom sediment at equally spaced verticals in a sampling section. Sampling is done with a hand-operated dredge. All sediment collected at a section is composited and radiochemically analyzed (Cottrell, 1959). The longitudial distribution of cesium–137, determined from the 1962 monitoring survey, is compared to the distribution determined from this inventory in figure 10.

VERTICAL DISTRIBUTION

Radionuclide concentrations are related to sediment thickness and location in the study reach. This relationship is shown in figure 11. The abscissa in the figure is the ratio of the thickness at a coring vertical to mean thickness in the sampling section (shown in fig. 12); the ordinate is the ratio of the concentration of cesium-137 in the core to its mean concentration in the sampling section (shown in fig. 9).

The increase in radionuclide concentration with relative thickness of sediment (fig. 12) may result from changes in the clay content of the sediment. Carrigan and others (1967) showed that the radionuclide concentrations increase as the clay content of the sediment increases. A linear regression analysis suggests that the clay-silt ratio increases as the relative thickness of the sediment increases (18 cores; correlation coefficient, 0.46; regression coefficient, 0.042).

CONTRIBUTION TO INVENTORY FROM REACHES OUTSIDE OF STUDY REACH

Some of the radioactivity in bottom sediments within the study reach may have been contributed by fallout from weapons tests. Fallout is transported into the study reach primarily by flow from parts of the Clinch River basin upstream from the head of the study reach.

Contributions to the radioactivity in bottom sediments of the study reach from fallout appear to be negligible. Concentrations of radionuclides in bottom sediment at a sampling section 2.0 miles upstream from the study

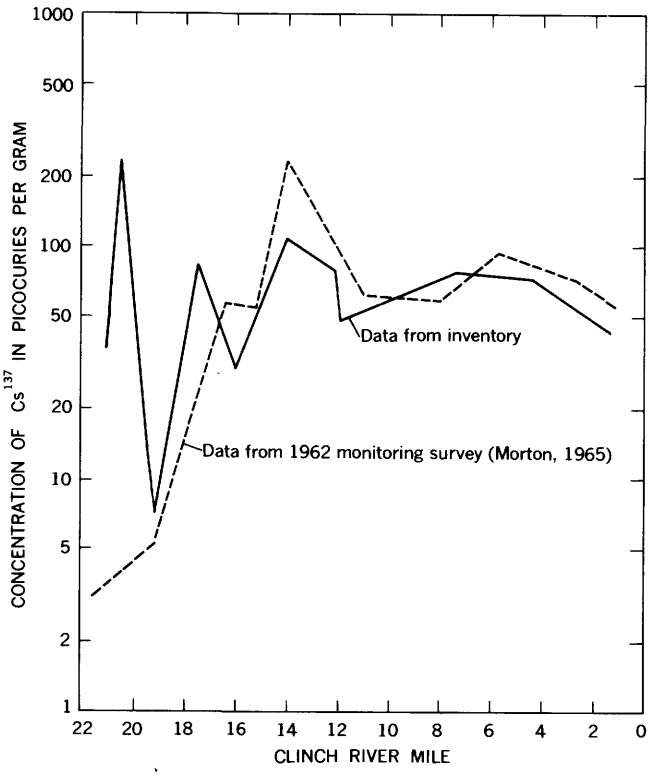

FIGURE 10.—Longitudinal distributions of cesium–137 in bottom sediment, determined through different sampling techniques, are much alike.

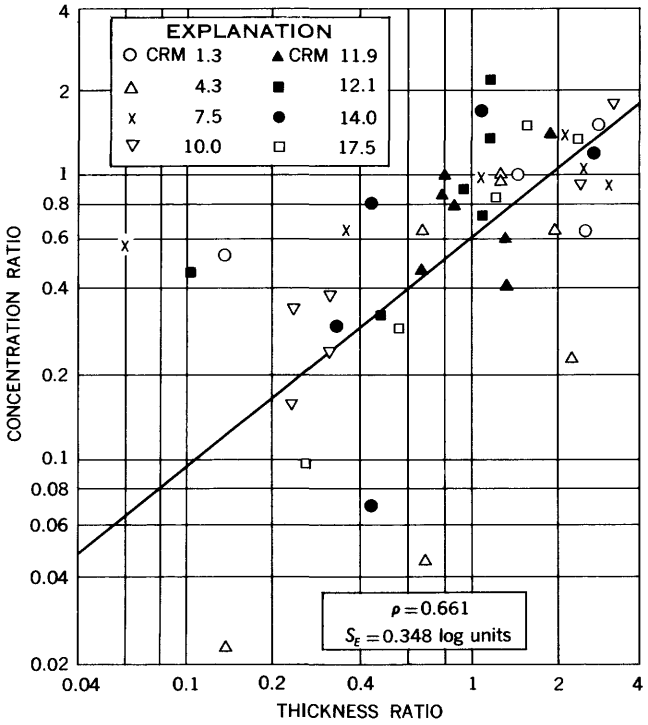

FIGURE 11.—Radionuclide concentration bears a nearly direct relationship to sediment thickness at specific sampling sections. Individual sectional relationships are a function of location in study reach. ρ is the coefficient of correlation for the logarithms of the concentration ratio and thickness ratio. S_E is the standard error of estimate.

reach, CRM 22.8, are below limits of detection. Concentrations of cesium-137 and cobalt-60 in waters flowing past a water-sampling station at CRM 41.5 have been at or below limits of detection. No rare earths have been detected in water samples collected at this station. Ruthenium-106 and strontium-90 have been detected regularly in water samples (Churchill and others, 1965); but these radionuclides constitute a minor fraction of the total inventory, and their retention factors are low.

Cores were collected in Poplar Creek and Emory River to gage the extent of upstream movement of contaminated waters from the Clinch River. Hydraulic conditions are such in the study reach of the Clinch River that upstream movement of water from the river can occur in any tributary.

Examination of gross gamma radioactivity scans of cores from Poplar Creek and from the section at mile 5.1 on the Emory River indicates that the radionuclide content in bottom sediments at these sampling sites (fig. 2) is negligible.

Concentrations of radioactivity in some cores from mile 1.9 on the Emory River were above lower limits of detection.

Pickering, in a study of radioactivity in bottom sediments of sloughs adjacent to Clinch River (Carrigan and others, 1967), noted that radiation levels in some areas approached levels measured at the surface of Clinch River bottom sediment.

Collectively, the evidence of radioactivity in bottom sediments in the lowermost reaches of tributaries to the Clinch River suggests that supplemental inventories might be undertaken.

DISTRIBUTION OF SEDIMENT

Ninety-five percent of the radioactive sediment in the Clinch River is downstream from CRM 15, and at least 60 percent is downstream from CRM 9 (table 4).

A tendency for mean thickness of radioactive sediment to increase linearly from the head of the study reach to the mouth of the Emory River (CRM 21.0 to 4.5) appears to exist (fig. 12). The general trend for increasing thickness may be explained by considering hydraulic conditions in the study reach. Accretions to flow in the study reach are almost negligible except inflow from the Emory River (U.S. Geological Survey, unpub. data, 1961). Flow area continuously increases in the downstream direction (Morton, 1962a). Without accretions to flow and with increasing flow area, velocity and intensity of turbulence of the stream decrease and consquently sediment transport capacity decreases in the downstream direction.

A decrease in mean thickness of radioactive sediment

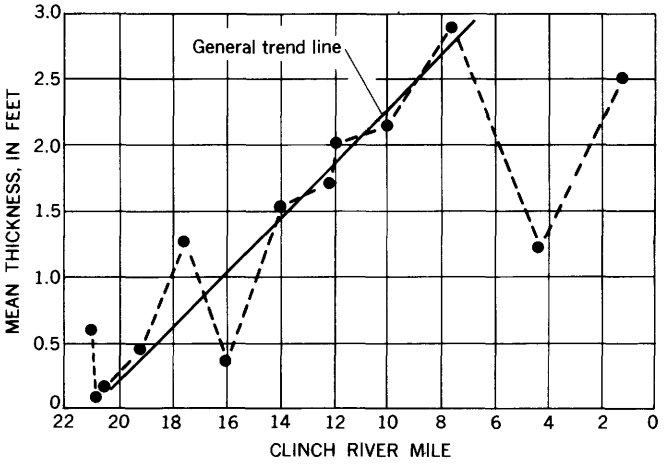

FIGURE 12.—Radioactive sediment thickness increases in the downstream direction as a result of increasing flow area.

of more than 50 percent occurs between sampling sections upstream at CRM 7.5, and downstream, at CRM 4.3, from the mouth of the Emory River. This decrease in sediment thickness may be the result of a localized increase in turbulence due to inflow from the Emory River and (or) the diversion of Clinch River upstream into the Emory River (Elder and Dougherty, 1958). An increase in turbulence would tend to keep sediment particles in suspension.

At the mouth of Poplar Creek (CRM 12.0), the mean thickness of radioactive sediment sharply increases. Probably the decrease in radionuclide concentrations observed in this part of the streambed is due to dilution of radioactive sediment with uncontaminated sediments issuing from the creek.

The section at which sediment transport capacity rapidly decreases is clearly indicated to be at CRM 14.0 in figure 13. From CRM 21.0 to 14.0, deposition is limited to zones of the channel near bank(s) of the river (Pickering, 1969). The sediment transport capacity is of much greater magnitude in the central core of flow in this reach than near the banks. Though the magnitude of transport capacity remains greater in the central core of flow than elsewhere in the flow area throughout the study reach, its magnitude relative to that near the banks drops sharply in the vicinity of CRM 14.0.

The cross-sectional area of radioactive sediment is at a maximum at CRM 10.0 (fig. 13) because of the influence of islands and submerged ridges on the flow pattern in that vicinity (Carrigan and others, 1967, p. 27).

During the 19½-year period of waste disposal (December 1943 to July 1962), 64 percent of the streambed has become covered with radioactive sediment. Areal distribution of radioactive sediments, for selected thicknesses, is listed in table 5.

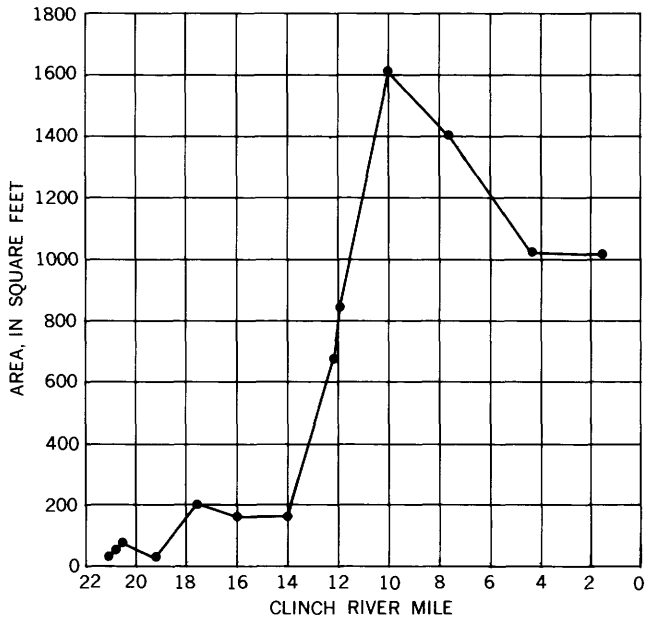

FIGURE 13.—Cross-sectional area of radioactive sediment increases most rapidly between CRM 14 and 10. Minor longitudinal variations occur upstream from this reach. An appreciable decrease in area begins at CRM 10.

TABLE 5.—*Areal distribution of radioactive sediments, for selected thicknesses*

Radioactive sediment thickness, in feet	*Proportion of radioactive surface area over which indicated thickness is equaled or exceeded*
1. 0	0. 57
1. 5	. 41
2. 0	. 31
2. 6	. 24
4. 0	. 13

PHYSICAL PROPERTIES

Three physical properties of Clinch River bottom sediment that were measured are specific bulk weight, dry-to-wet weight ratio, and particle-size classification. Measurements of these characteristics have been restricted to radioactive zones in the sediment.

Mean specific bulk weight for all core composites is 100 pounds per cubic foot. Mean wet-to-dry weight ratio for all composites is 0.69. The dominant particle-size classification is silty clay based on the triangular-plotting method of Shepard (1954). Results of extensive physicochemical analyses of radioactive sediment samples obtained in the 1962 coring program are reported by Pickering (1967).

FUTURE ESTIMATION OF RADIONUCLIDE LOADING

Continued decline of radionuclide releases to the Clinch River in recent years (see table 1) indicates that increasing radiation hazard in the future is unlikely. Cowser and Snyder (1965) found that, even if releases continue indefinitely at the highest experienced levels (in 1956 or 1959), bottom sediments will remain a minor source of radiation exposure. With continuing decline of releases, further estimation of radionuclide loading in the sediments is not needed.

Waste disposal processes or quantities of wastes processed at ORNL could change such that releases to the river will increase. If releases of cesium-137, cobalt-60, and (or) rare earths should increase substantially above experienced levels for sustained periods, another safety analysis of radiation dosage from bottom sediment would be needed.

Safety analysis may be undertaken at two times: (1) after a period of increased loading to determine resultant radiation dosage and (2) prior to increased loading to estimate concentration and duration of releases which will assure safety.

For case 1, knowledge of retention factors would be an aid in estimating the magnitude of radiation dosage resulting from increased releases. The relationship of radiation dose to concentration of radionuclides in the release is

$$D = \tfrac{1}{2}(51.2)\ k_r\ \overline{C}\ E\ f,$$

in which D is the dose rate, in rad per day, for beta or gamma radiation from an infinitely thick source uniformly spread over the bed of the study reach; k_r is the retention factor in dimensionless units; $\overline{C}$ is the mean concentration of the radionuclide released for a known duration, with effects of radioactive decay taken into account, in microcuries per gram (10^{-6} curies per gram); E is the effective absorbed radiation of beta disintegration or maximum energy of gamma-ray emission, in million electron volts; and f is the fraction of distintegration of a particular energy, dimensionless. This equation for dose rate is derived from those proposed by Cowser and Snyder (1966; their eqs 14 and 17).

D is a nominal dose rate applicable to the study reach as a whole. As such, it is an indicator of relative hazard. If D approaches one-third of the critical dose rate, local dose rates may be approaching critical levels. Especially critical areas of the riverbed are along the right bank between CRM 20 and 21 and also in the vicinity of CRM 4.3, 14.0, and 17.5.

For case 2, safety analysis would seek an estimate of the rate of buildup of radiation to the critical dose rate. Radiation dose at the surface of the sediment increases, in general, as the radioactive sediment becomes thicker. If the radionuclide releases are constant, this relationship between radiation dose and thickness is an exponential function. Cottrell (1959, fig. 17) indicated that the dose asymptotically approached a maximum in Clinch River bottom sediment at a thickness of about 2.6 feet; Sayre and Hubbell (1965, p .47) found that this asymptote was somewhat less than 2.6 feet. This thickness (2.6 ft) was called the infinite thickness and its magnitude varied slightly with variations in physi-

cochemical properties of sediment and with energy distribution of gamma-ray emissions.

Rate of buildup of radiation dose depends on the rate of accumulation of radioactiver deposits; rate of accumulation, in turn, depends on location in the study reach.

Data required to estimate radiation dose would be the rate of accumulation, or time to attain infinite thickness, and the interrelationship of radionuclide concentrations in releases and sediments throughout the study reach.

Information on sediment distribution is obtained from table 5 and from figure 12. Time required to attain an overburden of infinite thickness may be estimated by assuming that the rate of accumulation at a point on the channel bed is constant. The rate is assumed to be equal to the ratio of the radioactive thickness observed at the point in 1962 to the period of radionuclide releases from Whiteoak Creek—19.5 years. Using this estimate of the rate of accumulation, the time required to attain infinite thickness over various proportions of the riverbed is shown in figure 14.

From the relationship of concentration and thickness, (fig. 11) the interrelationship of concentrations in releases and in sediment may be derived.

CONCLUSIONS

The inventory of radionuclides in Clinch River bottom sediment provides strong insight to the fate of radioactive waste released to the Clinch River. The inventory is a direct and the principal measure of the residual between the 20-year input and output loads of the radionuclides to the study reach of the river.

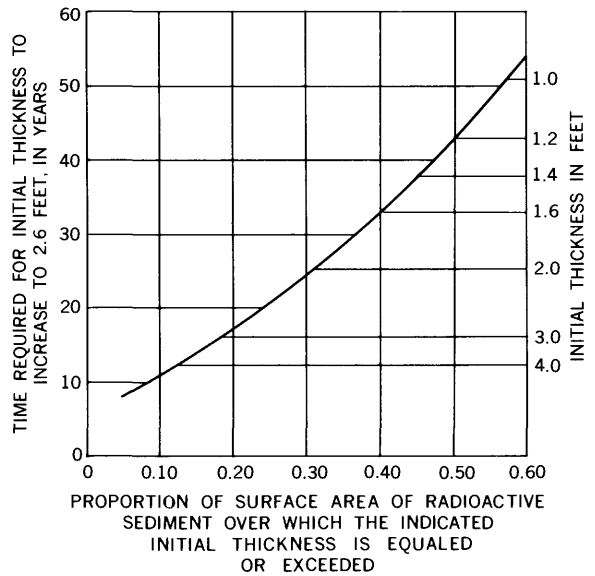

FIGURE 14.—An estimate of time required to accumulate 2.6 feet of sediment over a given proportion of surface area is made by assuming that the observed net accumulation continues at the same rate.

In the study reach, at least 20 percent of the cesium-137 and rare earths released to the river are retained in the bottom sediment. Retention of cobalt-60 releases is 9 percent. Less than 1 percent each of the ruthenium-106 and strontium-90 releases are retained in the bottom sediment. Most of the radioactive sediment is downstream from CRM 15. Because of downstream decreases in the turbulence of flow, the thickness, cross-sectional area, and volume per unit length of radioactive sediment are generally greater in the downstream parts of the reach than in the upstream parts. Of these three geometrical variables, only thickness varies in a regular manner, showing a linear increase in the downstream direction.

The total inventory of principal radionuclides in bottom sediment (cesium-137, cobalt-60, and rare earths) of the Tennessee River basin is undoubtedly greater than that measured in the Clinch River. Radionuclides have become associated with bottom sediment in sloughs and mouths of tributaries to the Clinch River and in the bed of the Tennessee River downstream from the mouth of the Clinch River (see Carrigan and others, 1967).

Two methods of aiding future safety analyses are suggested: (1) estimation of dose rates for individual radionuclides incorporated in bottom sediment by consideration of mean concentration of radionuclides in releases and of the retention factor, and (2) consideration of (*a*) rate of sediment thickness buildup in various areas of the study reach, (*b*) relation of concentration to sediment thickness, and (*c*) interelationship of concentrations in releases and in sediments.

Future use of the river for radioactive liquid-waste disposal is predicated on the safety of such practices. Present and past disposal practices have been safe (Cowser and Snyder, 1966) and, hence, have not limited usefulness of the river for such purposes. Continued decline in release of radionuclides would indicate that retention of radionuclides would not limit future usefulness. However, the possibility of an increase in radionuclide releases must be recognized. Assuming retention of 10 to 20 percent of some readionuclides in bottom sediment, a substantial increase in releases might be a factor leading to limited use of the stream for disposal of radioactive waste. Limitations resulting from an increase in radionuclide content of bottom sediment can be determined only through a safety analysis in which all avenues of radiation exposure are considered.

Water-sampling stations have value in obtaining continuous and current records of radionuclide concentrations at a site. However, measurements of small but significant losses or gains in radionuclide loads, occur-

ring between stations of a network, are difficult and costly. Inventory of accumulated radioactivity in sediment is inherently more accurate than determining a small residual between large radionuclide loads measured at two water-sampling stations. Cost of such an inventory would be comparable to the annual cost of operating a two-station water-sampling network in the Clinch River study reach. The techniques of radioactive sediment inventory developed in this investigation can be used for long-term surveillance of release of radioactive material. And an inventory can be used in lieu of water-sampling networks.

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